Effect of EGR on Emissions, Lubricating Oil and Wear in Diesel Engine

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

Master of Technology
in
Environmental Engineering and Management

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July, 2004

Certificate

It is certified that the work contained in the thesis entitled "***Effect of EGR on Emissions, Lubricating Oil and Wear in Diesel Engine***" by ***Shrawan Kumar Singh*** **(Y211717)** has been carried out under our supervision and this work has not been submitted elsewhere for the award of a degree.

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Dedicated

To

My Beloved Parents

Who have Sacrificed their Present for my Future

Acknowledgement

It is indeed a great feeling to remember my stay at IIT Kanpur. The intellectually stimulating work environment, incomparable facilities and unlimited opportunities for learning has encouraged me to do well in whatever I undertake.

It is with extreme respect and warm feelings that I wish to express my deep sense of gratitude and sincere regards to my thesis advisors, **Dr Avinash Kumar Agarwal** and **Dr Mukesh Sharma** for their earnest involvement, active guidance and impetus, without which this work could not have seen the light of the day. I feel fortunate to work under their supervision on an innovative and interesting research topic.

I am thankful to my teachers, Dr Vinod Tare, Dr Malay Chaudhuri, Dr D.K. Ghosh, Dr Purnendu Bose and Dr Soumyen Guha for help and guidance.

I wish to express my special thanks to my lab assistant Pathak ji, Rayis ji, Bhartiya ji and Yadav ji who helped me a lot during my engine run. I am grateful to Mishra ji, R.B.lal ji, and Vijay ji for their timely support and help, otherwise this research work would not be completed.

I specially thank to my friends Rajveer, Dhananjay and Bhawana whose company always made me cherish and comfortable during my stay at IIT Kanpur

I am thankful to my friends Subhankar, Prabhat sir, Devendra, Arun, Abhinaya, Indrani, Amita, Bharathi, Deepti, Major L.K.G.Singh and to my junior Deepak for their love, affection and support that made my stay at IIT Kanpur a wonderful experience.

I wish to thank my lab mates especially Varghese, Sumit, Sinha ji, Mirtunjaya, and Prakash whose company made me enjoyable to work with them. I am grateful to Mr P. Satvat, Mr Alok Sinha, Mr Pawan and Mr Manoj Tiwari for their continuous guidance and support.

I remember with reverence the encouragement and moral support from my parents, brothers and sisters who always remain behind the scene, but stood by me and provided support and inspiration through out this work, without which I would not have been able to reach this stage.

Last but not the least, I would like to express my gratitude to all my well wishers, the names of whom I have failed to include in this acknowledgement.

Shrawan Kumar Singh
July' 2004

Abstract

To meet stringent vehicular exhaust emission norms worldwide, several exhaust pre-treatment and post-treatment techniques have been employed in modern SI and CI engines. Exhaust Gas Recirculation (EGR) is a technique, which is being used widely to reduce and control the NO_x emission from diesel engines. However the use of EGR leads to rise in soot emission. This EGR generated soot leads to lots of other problems inside the engine like degradation of the lubricating oil, enhanced engine wear etc. In the present research work, an experimental investigation has been carried out to investigate the effect of EGR on emission pattern, lubricating oil and on wear of various vital engine parts.

A two cylinder, air cooled, constant speed DI engine of 9kW rating was used for the experiments. An experimental setup of employing EGR was setup on the engine and the test setup was run for 96 hours with a predetermined engine loading cycle using EGR and also without EGR (Under normal operating conditions). Temperature and smoke opacity of exhaust gas was measured to estimate the emission pattern. It was observed that with the use of EGR, percentage reduction in exhaust gas temperature was more than percentage increase in soot.

The lubricating oil of the engine was analyzed for metal addition after every 24 hours interval. Higher metal contents were found in the lubricating oil drawn from the engine using EGR. The generation of soot was qualitatively analyzed by taking pictures of in-cylinder engine parts. Higher carbon deposits were observed on the parts from the engine operating with EGR.

Higher wear was observed on piston rings of engine operated with EGR. The wear of cylinder liner was more at BDC compared to the TDC in EGR operated engine whereas in the normally operated engine (Engines without EGR), higher wear was observed at TDC. The possible reason of high metal content in lubricating oil and higher wear in the EGR system may be the high soot content in the lubricating oil from the engine employing EGR.

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Abbreviations

AAS	Atomic Absorption Spectrometry
A/F	Air/Fuel Ratio
BDC	Bottom Dead Center
BSFC	Break Specific Fuel Consumption
CI	Compression Ignition
C_d	Coefficient of Discharge
DI	Direct Injection
DPNR	Diesel Particulate NO_x Removal
EGR	Exhaust Gas Recirculation
GI	Galvanized Iron
IC	Inorganic Carbon
IDI	Indirect Injection
MATES	Multiple Air Toxic Exposure Study
NO_x	Nitrogen Oxides
PM	Particulate Matter
SOF	Soluble Organic Fraction
SCR	Selective Catalytic Reduction
TBN	Total Base Number
TDC	Top Dead Center
TOC	Total Organic Carbon
USEPA	United States Environmental Protection agency
ZDTP	Zinc Di-Thio Phosphate

CHAPTER 1

INTRODUCTION

Over the past few decades, diesel technology has significantly improved. As a result, diesel cars are faster, more efficient, drive better and are quieter than ever before. Not surprisingly, therefore, diesel sales continue to grow rapidly. It is expected that approximately one out of three new cars sold in Europe will be powered by a diesel engine. Based in large part on these high diesel engine sale and in anticipation of additional growth in the future along with future fuel efficiency improvements, European car makers have committed to a 25% improvement in light duty vehicle fuel economy by 2008 compared to 1995 [1].

At the same time, regulatory officials around the world continue to be concerned about diesel vehicle emissions, particularly about nitrogen oxides and particulates. Ozone, a by-product of nitrogen oxides and hydrocarbons, and nitrogen dioxide remain persistent air pollution problems in many parts of the world.

In late 2000, the US EPA summarized available information to characterize the cancer and non cancer health effects from exposure to diesel exhaust emissions in its draft Health Assessment Document for diesel engine emissions (the assessment) [2]. Based on the available information, EPA concluded that diesel particulate is a probable human carcinogen. The most compelling information to suggest a carcinogenic hazard is the consistent association that has been observed between increased lung cancer and diesel exhaust exposure in certain occupationally exposed workers working in the presence of diesel exhaust. The health problems associated with the diesel exhaust was brought into focus in the Multiple Air Toxics Exposure Study (MATES), a land mark urban toxics monitoring and evaluation study conducted for the South Coast Air Basin. In the monitoring program, over 30 air pollutants were measured including both gases and particulates. The key result of the MATES was mobile sources (e.g. cars, trucks, ships, aircrafts, etc.) represent the greatest contributor of the air pollution. About 70% of all risk is attributed to diesel exhaust emission, about 20% to other toxics associated with mobile sources (including benzene butadiene, and formaldehyde), and about 10% of all risk is attributes to stationary sources [1]. Hare, detected significant amount of metals such as Fe, Si, Cu, Zn, Ca, Ni, Pb, and P in diesel engine exhaust [3].

As a result, environmental agencies have continued to dramatically tighten exhaust emission standards. The serious and growing concern regarding diesel vehicle emissions has been accelerated around the world to get low harmful exhaust. The new particulate matter standards represents 90% reduction for most heavy duty diesel engines from current PM standard and is projected to require addition of highly efficient PM traps to diesel engines. The new NO_x standard is projected to require the addition of highly efficient NO_x emission control system to diesel engines. Authorities in the USA, Japan, and Europe as well as in India have imposed legislation aimed at controlling exhaust emissions from diesel exhaust emissions [4]. Reducing NO_x emission from the medium and heavy duty diesel engines primarily used for commercial vehicles is historically achieved by retarding the injection timing with consequent penalties in fuel consumption. Looking to future, with dual requirement for reduced NO_x and improved fuel consumption for lower CO_2 emissions, it is clearly desirable that an alternative to injection retard for NO_x control should be developed. Without a technological breakthrough the required drastic NO_x reduction will deteriorate fuel economy and increase the engine cost considerably. Studies are still on progress for developing methods for reducing the NO_x emission by exhaust after-treatment e.g. Selective Catalytic Reduction (SCR), NO_x traps etc. [5]. Whilst successful in controlling the NO_x, such systems are not yet usually used for automotive applications as these systems suffer from logistics problems. Exhaust Gas Recirculation (EGR) is one of the most useful techniques for controlling the NO_x emission for automobiles and this solution has been successfully applied in production for light duty/ heavy duty diesel engines. In heavy duty application, the use of EGR has not been extensively researched.

1.1 Exhaust Gas Recirculation

Controlling the NO_x emissions primarily requires reduction of in-cylinder temperatures and this is achieved by retarding the injection timing and by water injection in the combustion chamber with a high amount of penalties in engine performance and durability. To get an alternative way of reducing the NO_x emission, EGR has been used by several researchers including Abd-Alla, Baret, Ladommatos [6-10]. Substantial control on NO_x emission is achieved by EGR. It has found that dilution of intake charge by inert gases, NO_x control is possible.

The most effective NO_x control has been achieved by using the diluents with high specific heats. EGR involves replacement of oxygen and nitrogen of fresh air, which is entering in the combustion chamber through the inlet manifold with the carbon dioxide and water vapor from the engine exhaust. Since the specific heat of both carbon dioxide and water vapor is greater than that for oxygen, exhaust gases were found effective diluents in an internal combustion engine. In addition, a reduction in the oxygen concentration at the flame region leads to reduction in flame temperature. These reductions in the flame temperatures lead to reduction in the NO_x formation rate and NO_x emission in the exhaust. So EGR can be conveniently considered for NO_x control. But this reduction of NO_x leads to penalties in BSFC, particulate matter emission and the wear of the various parts of the engine, which needs control and further investigations.

1.2 Performance of Engine Using EGR

Diesel engines are normally operated at partial load. The A/F ratio is quite lean hence large EGR can be used without significant penalties in fuel consumption, particulate matter emission etc. In heavy duty engines, the NO_x produced during high load operation is substantially high. Applying EGR at or near full load tends to increase the smoke emissions since engine operates near stoichiometric air fuel ratio. This not only increases the particulate emission but may also necessitate de-rating of the engine to maintain acceptable smoke levels.

EGR results in reduction of oxygen to fuel ratio, which leads to rise in soot emission level. The reduction in oxygen availability in the burning regions of the combustion chamber impairs the soot oxidation process along with reduction in local flame temperature, which ultimately causes a rise in soot emission. The rise in smoke level or in other words rise in soot level of engine exhaust due to EGR, effects the engine performance in various ways. The increased soot level causes considerable increases in the wear of the various vital engine parts. Abnormal wear with EGR showed characteristics of corrosive wear, which may be because of the acids present in exhaust gases. However it has not been yet clearly understood, why the engine with EGR suffers unusually high degree of such corrosive wear compared with the engine without EGR.

The particulate matter mainly contains the elemental carbon. Along with that in a soot particle, some amount nitrates, sulfates, silicates, metals and the organic carbon are also

attached to the elemental carbon. These soot particles have diameter of ranging from 0.01μm to 0.8μm, while the boundary layer oil film thickness is about 0.001μm to 0.05μm only. The boundary lubrication occurs at top dead centers and bottom dead centers, so these are the prime location of wear due to these soot particles.

The determination of metals in lubricating oil has found wide application e.g. in the preventive maintenance of oil wetted mechanism (analysis of wear metals), in control of various lubricant additive in depleted oils, for checking of toxic elements during liquidation of used oils and for disposal of used lubricating oils. It has been found that in a normal engine operation the amount of metals present in the lubricating oil as additives initially reduces with the engine operation due to their consumption but after certain time of engine operation the concentration of most of the metals increases due to addition of metallic wear debris from the engines.

1.3 Objectives of the study

The main objective of the study is to evaluate the performance of the direct injection diesel engine using Exhaust Gas Recirculation. The study has been carried out in three major sub areas.

1. Change in the exhaust emission pattern of the engine using EGR
2. Change in the wear pattern of the engine using EGR
3. Soot loading and the lubricating oil degradation of the engine using EGR

CHAPTER 2

HISTORICAL PERSPECTIVE

The vehicular pollution has emerged as one of the major concern affecting the society. Today, there are about 46 million motor vehicles registered in India. The vehicle population by 2010 is estimated to grow to 141 million, while the scope for increasing the road length is limited.

The diesel engine is most efficient prime mover commonly available today for decentralized stationary and transport applications. Diesel engines move a large portion of world's goods, power much of the world's equipment, and generate electricity more economically than any other device in their size range. But diesel is one of the largest contributors to environmental pollution problem worldwide, and will remain so with large increase expected in vehicle population and mileage. Diesel emissions contribute to diseases like cancer, cardiovascular and respiratory health effects pollution of air, water, and soil, reductions in visibility, and global climate changes [11].

2.1 Combustion in Compression Ignition Engines

In a basic diesel cycle air alone is compressed to a high pressure and temperature during the compression stroke. The air supply in a CI engine is essentially constant for a given speed, and changing the quantity of fuel injected changes the A/F ratio. Prior to TDC the fuel is injected into the combustion chamber by means of an injector and ignition occurs when the fuel vapor and air mixture reaches to auto ignition temperature. The total quantity of fuel injected is controlled by the load and speed of the engine. The fuel–air ratio of the diesel engine varies from 0.01 to 0.06, which corresponds to A/F ratios of from 100:1 to 15:1. Thus the A/F mixtures for the diesel engines are much leaner. The A/F ratios in the various parts of the chamber vary widely. Combustion occurs in several locations within the chamber simultaneously, so in a CI engine, localized combustion occurs. When the amount of fuel is increased and the chemically correct A/F ratio is approached, the CI engine begins to produce a noticeably black smoke. This is due the fact that in certain areas within the chamber, the A/F ratio will be so rich that some of the carbon and oxygen particles will be unable to combine in the time allotted for combustion. These un-combined carbon particles are the cause of the engine smoke. At idling, light "whitish" smoke may appear. Under

these operating conditions, lower temperatures in the combustion chamber, plus less turbulence, may result in only partial burning of some of the fuel particles with consequent smoky and unpleasant smelling exhaust [12].

Due to these practical limitations caused by smoke, CI engines are operated at A/F ratios leaner than the chemically correct ratio. The additional amount of air above that required for the stoichiometric ratio is termed excess air. The goal of CI engine designer is to utilize, through combustion, as much of the trapped oxygen in the combustion chamber as possible, thereby reducing excess air to a minimum.

The fuel does not ignite immediately upon injection into the combustion chamber. There is definite period of apparent inactivity between the times when first droplet of fuel hits the hot air in the combustion chamber, and the time when starts through the "actual burning" phase. This period is known as "ignition delay". For excellent working of CI engine, the fuel should have shorter ignition delay.

2.2 Emissions from Diesel Engines

In diesel engines, fuel is injected into the cylinder just before end of compression stroke, so in combustion chamber the fuel distribution is non uniform. The pollutant formation processes are strongly dependent on the fuel distribution and how that distribution changes with time due to mixing. The major concentration in the diesel engine exhaust is of CO_2, H_2O, N_2 and O_2 along with them CO, HC, NO_x and soot are found in smaller quantities. The main pollutants of concern from diesel engines are NO_x and Particulate matter. NO forms in the high temperature burned gas regions in the combustion process and soot forms in the rich unburned fuel containing core of the fuel sprays, within the flame region, where the fuel vapor are heated by mixing with hot burned gases. Soot then oxidizes in the flame zone when it comes in contact with oxygen, giving rise to the yellow luminous flame. Hydrocarbons originate in region where the flame quenches both on the walls and where excessive dilution with air prevents the combustion process from either starting or going to completion.

2.2.1 Oxides of Nitrogen

At a given temperature and pressure, chemical equilibrium can exist when the formation and decomposition of NO are equal. When equilibrium is attained, the concentration of NO remains stable, and depends on the number of factors, including temperature, pressure, and the amount of other species present. In an internal combustion engine, the equilibrium concentration of NO at a given location in the

engine cylinder changes continuously, because the continuous change in pressure, temperature, and the concentration of various other species. The fuel air mixing and combustion processes are extremely complex. During the premixed or uncontrolled diesel combustion phase, immediately following the ignition delay, fuel air mixture with a spread in composition about stoichiometric burns due to spontaneous ignition and flame propagation. During the mixing controlled combustion phase, the burning mixture is likely to be closer to stoichiometric.

NO_x is used to denote the total concentration of NO and NO_2. NO accounts for the bulk of NO_x concentration. The maximum value of (NO_2/ NO_x) for diesel engines can vary from 10 to 30% depending on engine load and speed [13].

The NO formation and decomposition from atmospheric nitrogen can be described by the extended ***Zeldovich Mechanism*** [13]. The principal reactions at near stoichiometric fuel - air mixture governing the formation of NO from molecular nitrogen are,

$$O + N_2 \rightarrow NO + N \qquad (2.1)$$

$$N + O_2 \rightarrow NO + O \qquad (2.2)$$

$$N + OH \rightarrow NO + H \qquad (2.3)$$

$$NO + HO_2 \rightarrow NO_2 + OH \qquad (2.4)$$

$$NO_2 + O \rightarrow NO + O_2 \qquad (2.5)$$

The initial rate controlled NO formation (i.e. when [NO]/ $[NO_2]_e$ << 1) can be described by the following expression. In the expression [ ] denotes the molar concentration of the species and $[\ ]_e$ denotes the equilibrium concentration [13].

$$d[NO] / dt = (6 \times 10^{16} / T^{0.5}) \exp(-69090/T)\, [O_2]_e^{0.5}\, [N_2]_e \quad mol/cm^3.s \qquad (2.6)$$

The sensitivity of the NO formation rate to temperature is evident from this expression. The critical time period of NO_x formation is when burned gas temperatures are at a maximum, i.e. between the start of combustion and shortly after the occurrence of peak cylinder pressure. After peak pressure, burned gas temperatures decrease as cylinder gases expand. Expansion lead to decrease in temperature and mixing of high temperature gas with air or cooler burned gas stops the formation of NO_x.

2.2.2 Particulate Matter

Diesel particulates consist of combustion generated carbonaceous material (soot), on which, some organic compounds have been adsorbed. Most PM result from incomplete

combustion of fuel hydrocarbon. Some of the PM formation is contributed by the lubricating oil combustion.

Diesel exhaust particles mainly consists of highly agglomerated solid carbonaceous material, ash, volatile organic and sulfur compounds etc. A representative composition and structure is illustrated schematically in figure 2.1. Solid carbon is formed during combustion in localized fuel rich regions. Much of it is subsequently oxidized. The residue comes out in exhaust in the form of solid agglomerates. A tiny fraction of the fuel and atomized and evaporated lubricating oil escape oxidation and appear as volatile or soluble organic compounds (SOF) in the exhaust. The SOF contains polycyclic aromatic compounds containing O_2, N_2, and sulfur.

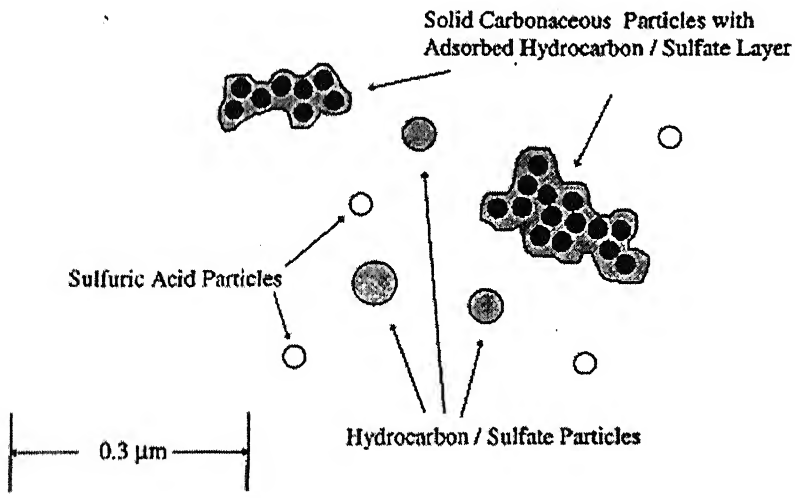


Figure 2.1: Typical Structure of Engine Exhaust Particles [14]

Most of the sulfur in the fuel is oxidized to SO_2, but a small fraction is oxidized to SO_3 which leads to formation of sulfuric acid and sulfates in the exhaust. Metal compounds in the fuel and lubricating oil lead to a small amount of inorganic ash. Figure 2.2 shows typical composition of particulate matter for a current technology diesel engine. The sulfuric acid / sulfate fraction is roughly proportional to the fuel sulfur content. The fraction associated with unburned fuel and lubricating oil (SOF) varies with engine design and operating conditions. It can range from less than 10% to more than 90% by mass [14]. SOF values are highest at light engine loads when exhaust temperatures are low.

The composition of exhaust particles depends upon where and how they are collected. As the exhaust is diluted and cooled, nucleation, condensation, and adsorption

transform volatile materials to solid particulate matters. In the tail pipe, where the temperatures are high, most of the volatile materials are in gaseous phase.

Soot Particle Formation: For the formation of soot particles, several different theories are available to explain the pyrolysis process, i.e. the decomposition and atomic rearrangement of the fuel molecules that culminates in nucleation. The widely accepted mechanism is thermal cracking that result in fragmentation of the fuel molecules into smaller molecules, condensation reactions, polymerization (which lead to formation of larger molecules) and dehydrogenation that lowers H/C ratio of the hydrocarbons, which form soot.

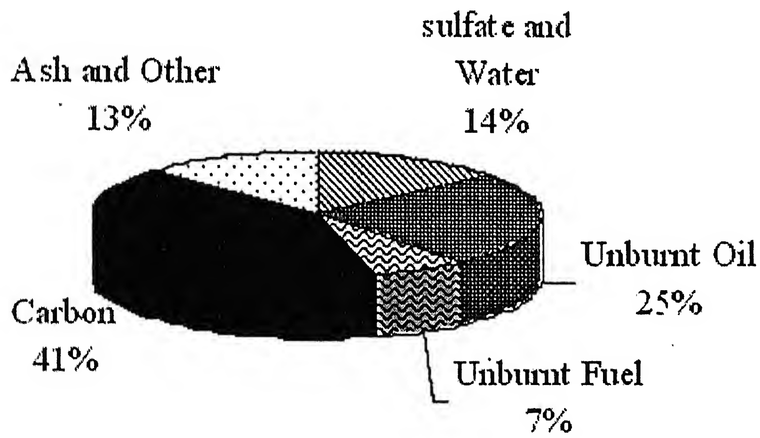


Figure 2.2: Typical Composition of Particulates Matter from Diesel Engines [14]

Three different paths to production of soot appear to exist, depending on the formation temperature. At the lowest temperature ($\leq$ 1700 K) only aromatics or highly unsaturated aliphatic compounds of high molecular weight are effective in forming solid carbon through pyrolysis. At intermediate temperatures, typical of diffusion flames ($\geq$1800 K), all normally used hydrocarbon fuels produce soot if burnt sufficiently rich, but appear to do so by following a different path. At very high temperatures, above the range of interest for diesel combustion, nucleation seems likely that involves carbon vapor as the formation mechanism for soot [14].

2.2.3 Hydrocarbon

There are two major reasons of HC emissions from diesel engines under normal operating conditions.

(a) Over leaning of the fuel injected during the ignition delay period is a significant source of hydrocarbon emission, especially under conditions when the ignition delay is long. As soon as fuel is injected in the cylinder, a distribution in the fuel/air

equivalence ratio across the fuel sprays develops. The amount of fuel that is mixed leaner than lean combustion limit increases rapidly with time. The fuel close to spray boundary mixes beyond the lean limit of combustion and does not auto ignite or sustains a fast reaction front. Within this region, unburned fuel, fuel decomposition products, and partial oxidation products exist and some of these escape the cylinder without being burned.

(b) There are two sources of fuel entering the cylinder during combustion and results in HC emissions due to slow or under mixing with air. One is fuel that leaves the injector nozzle at low velocity, often late during combustion process. The second source is the excess fuel that enters the cylinder under over fuelling conditions.

2.3 Potential Solutions for Emission Reduction from Diesel Engines

Initial engine development efforts aimed at reducing emission focused on reducing NO_x emissions by retarding the fuel injection process. When no other action is taken, this results in an increase in PM emission and/ or BSFC, as is commonly visualized in the familiar trade off between PM, BSFC and NO_x. To avoid this, the manufacturers of diesel engines have introduced advanced engine features, which shift the trade off to much lower NO_x and PM emission levels while maintaining acceptable fuel consumption levels.

Some new technologies have been identified, which differ from this solution. They no longer aim to improve the emission trade off by influencing the physical processes of fuel injection and air admission. Instead, they aim to reduce emission by directly influencing the chemistry of the combustion process (i.e. through different fuel formulation, water injection or charge composition) or by catalytic after treatment of the exhaust gases [7].

2.3.1 NO_x Reduction

NO_x reduction from a diesel engine exhaust can be achieved by treating the exhaust and/ or by decreasing its formation in the cylinder. The exhaust gas is passed through the De-NO_x catalyst (Selective Catalytic Reduction, SCR) to reduce the oxides of nitrogen. In the traditional SCR systems, NO_x (mainly NO) is converted by ammonia to form nitrogen and water. Miller experimented on SCR system, using NO_x sensors to analyze the exhaust. They achieved up to 87% reduction in NO_x and 100% elimination of hydrocarbons [15].

$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2 \quad (2.7)$$

$$4NH_3 + 3NO_2 \rightarrow \frac{7}{2}N_2 + 6H_2O \quad (2.8)$$

$$NH_3 + 6NO \rightarrow 5N_2 + 6H_2O \quad (2.9)$$

Despite its advantages, the SCR technology faces some critical detriments to its catalytic performance such as catalyst surface passivation (caused by deposit formation) and consequent stoichiometric imbalance of the urea consumption [5]. Deposit formation deactivates catalytic performance by not only consuming part of the ammonia produced during urea decomposition but also degrading the structural and thermal properties of the catalyst surface. Along with that Urea is a hazardous compound and it has limited availability, hence it is not feasible to use SCR in Indian conditions successfully.

NO_X adsorbers are also used for trapping the NO_X in the exhaust pipe. But these adsorbers are sulfur sensitive. NO_x adsorbers offer a high potential to decrease the NO_x emissions from automobiles. These NO_x traps contain a precious metal to behave as a three-way catalyst under rich conditions and a storage component from the groups of alkali, alkaline-earth metals or rare earths. During the lean phase corresponding to nitrate formation, stable sulfates (produced from the presence of sulfur in the exhaust gases) are formed, leading to a progressive poisoning of the NO_x adsorber. So desulfation techniques are being developed to trap the fuel sulfur. Li, used NO_X adsorber in light duty engine and achieved more than 90% NO_X reduction [16].

Exhaust Gas Recirculation (EGR) is another very effective technique of reducing the emission of NO_X from the diesel engine exhaust. But the rise in EGR level increases the amount of formation of soot particles with a penalty in BSFC. For controlling the soot emission, the soot traps can be used. EGR increases the soot content in the lubricating oil, thereby increasing wear of the various vital engine parts. Various studies about the EGR systems have been described later in this chapter.

2.3.2 Particulate Matter Reduction

Various types of filters have been used for the collection of particulate matter so that they can be trapped. The path of the particulate matter is being restricted so that their dispersion in the environment can be suppressed. It has been found that filtration efficiency is high for most of the filter types, like ceramic wall-flow, fiber, metal or ceramic foam, etc., as long as the effective filter pore opening is less than perhaps 40 to 80 μm [17].

The ultimate diesel emission control solution should have simultaneous reduction in NO_x and soot. For this, particulate filters have been used with SCR or with NO_x traps. By these methods a substantial amount of emission reduction has been achieved. Reduction of PM emission in EGR systems has also been attempted by developing a low voltage soot removal device installed in EGR system, by multiple fuel injection system [18, 19]. Nakatani *et al.,* of Toyota Motor Corporation have developed a new after treatment system called DPNR (Diesel particulate- NO_x Removal System) for continuous reduction of PM and NO_x in diesel exhaust gas. A fresh DPNR catalyst reduced more than 80% of both NO_x and PM [20].

2.4 Exhaust Gas Recirculation (EGR) in Diesel Engines

The development of motive power plants units with low environmental impact has become one of the most interesting challenges in automotive technology. Diesel exhaust contains CO_2, H_2O, N_2 and O_2 in thermodynamically significant quantities and CO, THC, NOx and soot in thermodynamically insignificant but environmentally significant quantities. In modern Diesel engines, the combination of the former quantities normally comprise more than 99% of the exhaust, while the latter combination, the pollutants, accounts for less than 1%. Thus, the challenge is to minimize the pollutants by manipulating the thermodynamic properties and the oxygen concentration of the cylinder charge while keeping minimum degradations in power and efficiency, which is the principal reason to apply Diesel EGR [21]. In fact, partial recirculation of exhaust gas, which is not a new technique, has recently become essential, in combination with other techniques, for attaining lower emission levels.

EGR is an important technique used for control of NOx emissions from SI engine without penalties in other pollutants or excessive fuel consumption. However, applying EGR for NOx reduction in CI engines can result in substantial increase in particulates and smoke emission. Still EGR is one of the most effective techniques currently available for reducing NO_x emissions in IC engines. .

A fraction of the exhaust gases are recycled by a control valve from the exhaust system to the intake system. The recycled exhaust gases are mixed with the fresh air of the intake system. Diesel engines operate with no deliberate inlet air throttling (i.e. without a throttle). Thus, Diesel engines admit into the cylinders as much air as possible at a given engine running condition (say, 0.5 g as shown in figure 2.3). Thus, the application of EGR (say, 0.1 g as shown in figure 2.3) involves displacement of some

of the inlet air by EGR. Abd-Alla, summarizes that due to these consequence of this air displacement is a reduction in the oxygen available for combustion [6]. Since for a given torque and power output, the amount of fuel supplied to the engine must stay constant, the reduced oxygen available for combustion lowers the effective air–fuel ratio. This reduction in air–fuel ratio affects exhaust emissions substantially.

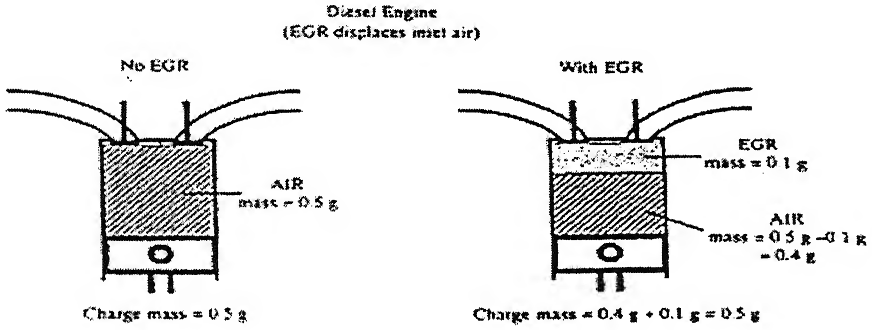


Figure 2.3: EGR Displaces Oxygen/ Air in CI Engine [6]

Figure 2.4 summarizes the effects of EGR on the inlet charge composition of a Diesel engine. In figure 2.4, 25% of the inlet airflow rate is removed and replaced by an equal volume flow rate of hot EGR. It can be seen that the effect on the inlet charge is, firstly, a 14% reduction in the charge mass flow rate. This is due to the reduction in the engine volumetric efficiency as a result of the rise in inlet charge temperature.

Secondly, some of the inlet air is displaced by carbon dioxide (CO_2) and water vapor (H_2O), which are the principal constituents of EGR. Thus, the application of hot EGR reduces the nitrogen (N_2) flow rate to the engine by about 15% and the oxygen (O_2) flow rate by19%. About one-fifth of the reduction in the O_2 flow rate is due to its displacement by CO_2 and H_2O present in the EGR, and the remainder is due to the reduction in volumetric efficiency. When EGR is mixed with the inlet air supplied to a diesel engine, the temperature of the inlet charge to the engine increases, which can also significantly affect the compressed charge temperature and the combustion process.

The EGR (%) is defined as the percent of the total intake mixture, which is recycled, exhaust [6],

$$EGR(\%) = \frac{M_{EGR}}{M_i} \times 100 \qquad (2.10)$$

Where, M_{EGR} is the mass of Recirculating exhaust gas and M_i is the mass of total intake air to the combustion chamber

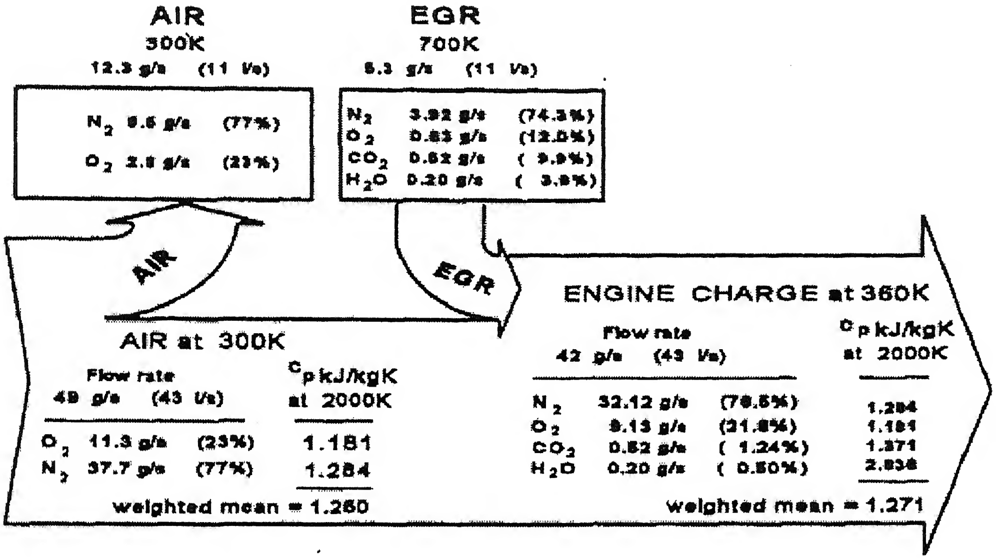


Figure 2.4: The Effect of EGR on Engine Inlet Charge [9]

An alternative definition of percent EGR is also used based on the ratio of CO_2 present in intake manifold and CO_2 in the engine exhaust [22],

$$\mathrm{EGR}(\%) = \frac{\left\{[CO_2]_{\text{inlet}} - [CO_2]_{\text{ambient}}\right\}}{\left\{[CO_2]_{\text{exhaust}} - [CO_2]_{\text{ambient}}\right\}} \times 100 \qquad (2.11)$$

Another definition of EGR (%) is given as [21],

$$\mathrm{EGR}(\%) = \frac{(CO_2)_{\text{intake}}}{(CO_2)_{\text{exhaust}}} \times 100 \qquad (2.12)$$

2.5 Classification of EGR Systems

The EGR systems are classified as, on the basis of EGR, temperatures, pressures, and configuration.

2.5.1 Temperature Basis

The implementation of EGR is straight forward for naturally aspirated diesel engines because the exhaust tailpipe's backpressure is normally higher than the intake pressure. When a flow passage is devised between the exhaust and the intake manifolds and regulated with a throttling valve, exhaust gas recirculation is established. The pressure differences are generally sufficient to drive the EGR of desired amount, (except during idling), whilst a partial throttling in the tailpipe itself can be activated to produce the

desired differential pressure. Based on this, the EGR systems are classified in following three categories [21],

1) Hot EGR
2) Fully Cooled EGR
3) Partly Cooled EGR

(a) Hot EGR: If the exhaust gas is recirculated directly to the intake resulting in increased intake charge temperature, the operation is called hot EGR.

(b) Fully Cooled EGR: Exhaust gas is fully cooled before recirculation into the combustion chamber by a water-cooled heat exchanger. In this case, moisture which is a combustion product, get condensed, and water droplets may enter the cylinder and produces undesirable effects, and corrosion inside the engine.

(c) Partly Cooled EGR: To avoid the water condensation, the temperature of exhaust gas is kept just above its dew point temperature and then the partly cooled exhaust gas is mixed with fresh air.

Zelenka *et al.*, [23] have reported that by applying partially cooled EGR in heavy duty diesel engines, EURO 3 emission standards can be achieved without using any after-treatment and without impairing fuel consumption.

2.5.2 Pressure Basis

Modern Diesel engines are commonly turbocharged, and the implementation of EGR is therefore, more difficult. When EGR is applied in such engines the durability and reliability of the engines must be maintained, which may require modification of the other engine components. On the basis of EGR pressures, EGR systems are classified as low and high pressure route systems.

(a) Low EGR Pressure Route System: In this system passage for EGR is provided from downstream of the turbine to the upstream side of the compressor of turbocharger (P_4-P_1>0) as shown in figure 2.5. Furthermore the tail pipe pressure P_4 can be elevated by partial throttling that ensures sufficient driving pressure for the EGR flow. This route passes the exhaust gas through the compressor and the intercooler, so the high temperature and the exhaust gas create fouling of these parts. In addition, the exhaust gases cause the charge air temperature to exceed the design temperature of the compressor and moreover, the pressure loss in intercooler increases after short time due to clogging. In low EGR pressure route systems, as the EGR ratio increases, a remarkable decrease in NO_x is achieved, but the black smoke and the fuel consumption increases significantly.

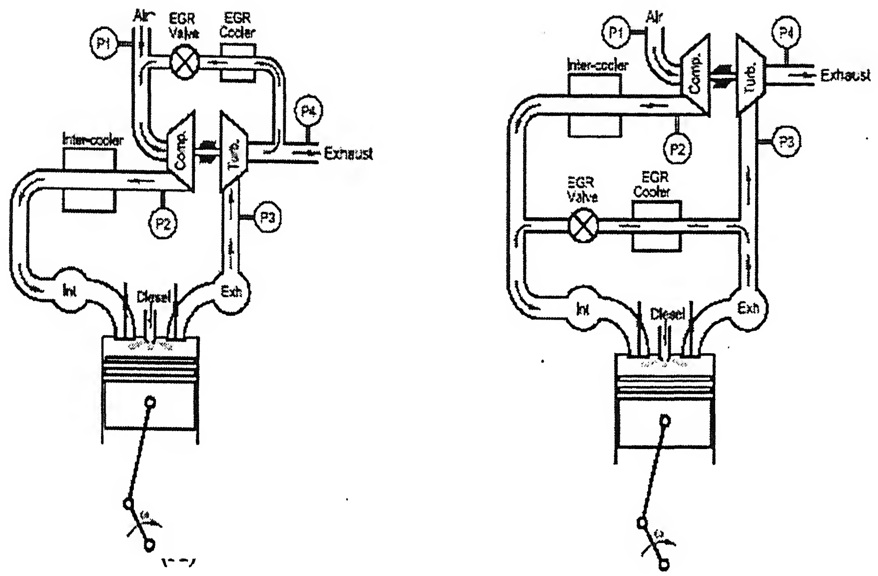


Figure 2.5: Low Pressure Route and High Pressure Route EGR Systems [21]

In this way, this system can be effectively utilized in high load regions with a significant reduction in NO_x emission. Although, this is an effective way of reducing NO_x emission, but before practical use, it is necessary to solve the problems related to durability of the compressor and fouling of the compressor. Efforts have also been made to route exhaust from the turbine outlet to inter cooler outlet directly, by passing the compressor.

(b) High EGR Pressure Route System: The exhaust gas is recycled from upstream of the turbine to downstream of the compressor (or downstream of the intercooler, if applicable). As shown in figure 2.5, the compressor and the intercooler are therefore not exposed to the exhaust; hence the problems encountered in the previous system are not present here. However, such a high-pressure loop EGR is only applicable when the turbine upstream pressure is sufficiently higher than the boost pressure, i.e. if $(P_3-P_2)>0$, prevails. The region of $(P_3-P_2)>0$ is limited to light load region, while in high load regions, it is difficult to maintain the $(P_3-P_2)>0$, so this method of EGR becomes impossible. To obtain the required differential pressure, several measures are offered, such as increasing the turbine back pressure, namely the outlet pressure of the turbine, and using a Variable Geometry Turbocharger (VGT). In this way EGR becomes possible in high load regions, the excess air ratio decreases and fuel consumption increases remarkably. Using VGT NO_x can be reduced greatly.

Kohketsu *et al.*, investigated the EGR systems on the basis of EGR pressures and found that high pressure EGR systems are more effective than low-pressure EGR systems [22]. With this method, the EGR area could be enlarged and NO_x can be reduced by up to 22% without increase in smoke emission or fuel consumption, while maintaining an adequate excess air ratio.

2.5.3 Configuration Basis

The EGR systems are classified in following ways on the basis of route length of the recirculatting exhaust gas as long and short route systems.

(a) Long Route EGR System (LR): In the LR system, the pressure drop over the intake air filter and the stagnation pressure in the exhaust gas stream are used to recirculate the exhaust gases. The exhaust gas velocity gives a small stagnation pressure, which in combination with the low pressure after the intake air filter gives the rise to a pressure difference to accomplish EGR.

(b) Short Route EGR System (SR): Short route system basically differs in the way of creating positive pressure difference across the EGR circuit. To control the charge temperature, this system requires coolers for the EGR gases, in addition to the regular intercooler. These EGR-coolers must be designed to withstand the aggressive exhaust gases.

Lundqvist *et al.*, have done a comparative study between different EGR systems for heavy duty diesel engines and their effect on performance, fuel consumption, and emissions [24]. They found that short route systems are generally more efficient than long route system, both in terms of NO_x reduction and fuel economy. They used a particulate trap and achieved low particulate and NO_x emissions but the durability of the particulate trap was a problem.

2.6 Effect of Exhaust Gas Recirculation on Engine Performance and Emissions

Exhaust Gas Recirculation is used primarily for reduction of NO_x. However, EGR results in an increase in particulate matters emission in diesel engines. A trade-off has been observed between NO_x and particulate matter emissions. Several measures have been taken to reduce the emission of NO_x and PM simultaneously by a number of researchers.

Stumpp *et al.*, reported that an engine running with EGR emits less exhaust gas than one without EGR [25]. Thus even if the concentration of toxic substances in the exhaust gas remains unchanged, the emission of toxic substances is reduced.

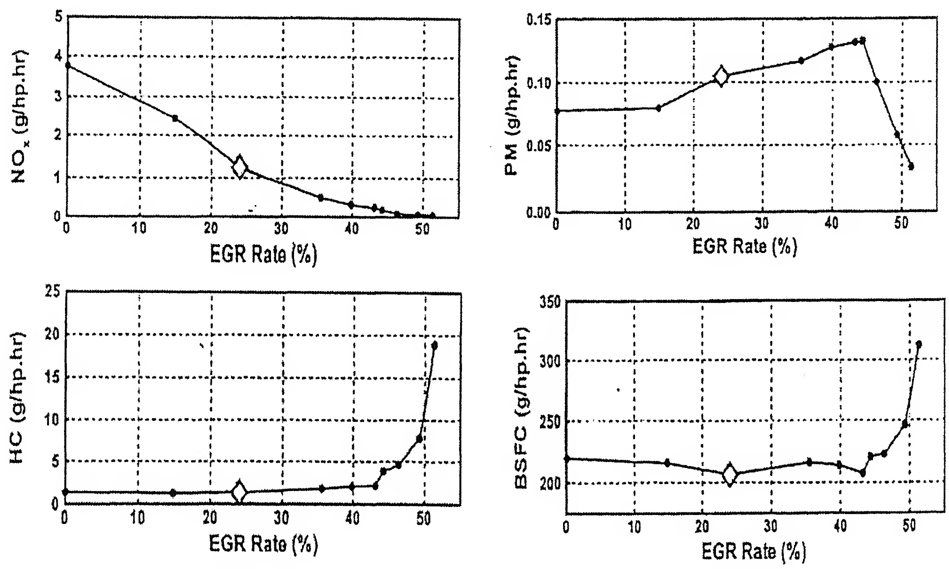


Figure 2.6: Effect of Rate of EGR on Emission of NO_x, PM, HC and BSFC

Wagner *et al.*, found that EGR rate up to 25% lead to reduction in NO_X emission without any significant increase in the soot emission [26]. But at higher EGR rates, the soot emission increases at faster rate, with a rapid decrease in NO_X emission. The most interesting result found was about the PM emission. The PM emission continuously increases up to 44% EGR. At this point, a further increase in EGR rate resulted in a significant decrease in PM emissions. Achieving simultaneously low NO_X and low PM resulted in a penalty (increase) in BSFC. The BSFC is not significantly affected at low EGR rates. These results are shown in Figure 2.6.

Plee *et al.*, varied the intake oxygen concentration of two single cylinder, divided chamber engines by adding nitrogen, argon, and oxygen while keeping the start of combustion fixed in order to study the effect of dilution on the exhaust emission [27]. They reported that major influence on NO_X emission is due to change in temperature rather than oxygen availability.

Ladommatos *et al.*, verified that EGR is an effective way of controlling the NO_X emissions from diesel engines [9]. Through the combination of increasing the heat absorbing capacity of the inlet charge and reducing oxygen availability for combustion, EGR reduces the flame temperature and the rate at which, the rate controlled NO_X formation reactions proceeds. Cooling of the EGR provides additional benefits by

lowering the NO_x emissions. It also improves the volumetric efficiency of the engine. Increase in inlet charge temperature always results in shorter ignition delay, [10]. The inlet charge temperature mainly affects the smoke and dry soot emissions. The effectiveness of EGR is enhanced considerably by cooling the EGR. The penalties of hot EGR are increased soot emission and, to a smaller extent, increased specific fuel consumption.

Baret *et al.*, found the solution for EGR systems and suggested a suitable pressure gradient for EGR flow could be achieved by using a turbocharger with variable nozzle guide vanes [7].

Needham *et al.*, reported that 20% EGR in a DI diesel engine reduced the NO_x concentration by more than 50%, with, a small decrease in the performance of the engine [4].

Zheng *et al.*, tested the EGR on various loading conditions and found that high EGR ratios are needed at low loads but low EGR ratios are sufficient at high loads [21]. When operating at low loads, diesel engines generally tolerate a higher EGR ratio because the exhaust contains a high concentration of O_2 and low concentration of combustion products CO_2 and H_2O. At high loads, the exhaust oxygen becomes scarce and the inert constituents become dominating along with the temperature of the exhaust gases. As a result, the NO_x production rates are also higher. As load increases, diesel engines tend to generate more smoke because of reduced concentration of oxygen. Rise in soot causes increase in wear of various engine parts. Corrosion was also observed due to sulfuric acid formation and condensation of water in recycled exhaust stream. Various studies have found deterioration of lubricating oil and excessive wear on valve train components even after 100 hours of using EGR [28, 29].

Doyle, reported that with EGR, the diesel engine oils get exposed to higher level of contamination which degrades the oil and damage engine parts [30]. Oil exposed to EGR environment show an increase in soot content, acid number and viscosity, while the engine and oils are both exposed to corrosive acidic gases and particle build up.

Gautam *et al.*, experimentally proved that diesel soot interacts with oil additives reducing its antiwear properties possibly by abrasive wear mechanism. Increased wear due to EGR is because of presence of soot in lubricating oil [28].

Yoshikawa *et al.*, installed a low voltage soot removal device at the air inlet in the EGR system to reduce the soot emission from the EGR systems and got 50 to 84% reduction

in soot emission [18]. The rate of deterioration of lubricating oil also decreases due to lower soot emission.

Pierpont *et al.*, studied the combined use of EGR and multiple injections and reported it to be very effective in simultaneously reducing particulate and NO_x emissions [19]. By using a 125 degree spray angle, an optimal triple injection and 6% EGR rate, particulate and NO_x were simultaneously reduced to 0.07 and 2.2 g/bhp-hr, respectively with a significant sacrifice in BSFC, mainly due to retarded injection timing.

2.7 Engine Wear due to EGR

EGR has proven to be effective technique for diesel engines. However, presence of increased levels of particulate matter in the exhaust lead to increased wear of engine parts such as cylinder liner, piston rings, valve train system and bearings. Wear of the materials could be due to chemical reactions taking place on the surface (adsorption, corrosion) or due to abrasion of material or anti wear film by soot particles. Soot particles get deposited at the interface between the piston and cylinder, and cause three-body wear. The three-body wear mechanism involves two surfaces and entrapped particles, and wear occurs at the particle-surface interface. The wear occurs when the decomposition products of the anti-wear additives get preferentially adsorbed on soot allowing metal to metal contact.

The commercially available lubricant oils are a combination of base oil and several additives, each of which is added in a desired amount to perform specific functions.

The most common additives in a lubricant are: (1) Viscosity Index (VI) improvers, which reduce the rate of viscosity change with temperature, (2) detergents and dispersants, which act as cleaning agents and (3) antiwear agents such as Zinc Di-Thio-Phosphate (ZDTP), which adsorb onto metallic surfaces and sacrificially provide chemical-to-chemical contact rather than metal-to-metal contact under high load conditions. Load, velocity, temperature, contact area, geometry and surface finish play a significant role in the friction and wear processes. Load plays a major role in wear testing as it directly influences the surface temperature and can affect the real contact area. Velocity also influences both the surface temperature and the fluid film thickness in lubricated applications. Surface finish of the wearing surfaces also plays an important role as it determines the regime of lubrication. Moderately rough surfaces allow more contact and greater probability of operating in the boundary lubrication regime.

Anti-wear additives e.g. zinc di-thio-phosphate (ZDTP), dispersant total base number (TBN) and detergent TBN is responsible for imparting key oil properties. Total Base Number is defined as the amount of acid (perchloric or hydrochloric) needed to neutralize all or part of a lubricant's basicity. Higher the base number, greater is the neutralizing capacity of the additive.

In a diesel engines, abrasion, adhesion, corrosion, scuffing and additive depletion are the main wear mechanisms. While abrasion, adhesion and scuffing involve mechanical damage of surfaces, corrosion and additive depletion involve a series of chemical reactions resulting in wear. Low-speed, high-load engine operations that occur during start-up, shutdown, and high torque conditions can starve the contact zone of the lubricant. This results in breakdown of the full oil film permitting contact between soot particles and the engine surfaces. This boundary layer is about 0.001 mm to 0.05 mm thick. However, soot particles have diameters ranging from 0.01 mm to 0.8 mm and could therefore, cause abrasive wear. Boundary lubrication occurs at the TDC and the BDC positions of the cycle and hence, maximum wear occurs at these positions.

Studies on valve train wear in the presence of soot were performed by Nagai *et al.*, [31]. As the EGR rate was varied from 0 to 17% to 25%, the wear of cam noses and rocker arm tips was found to increase significantly. Comparison of elemental analysis of the drain oil at the end of each EGR test run with the centrifuged oils indicated no evidence that elements such as zinc and phosphorous were eliminated. This suggested the following hypotheses of wear: (a) soot strips off the anti-wear film formed on the lubricated metal surface and the subsequent metallic contact itself accelerates the wear (b) soot might got changed to very hard particles under high-pressure conditions and might have acted as abrasive even to the metallic surfaces.

The role of carbon in mild lubricated wear was studied by Berbeizer *et al.*, [32]. They studied the influence of various factors like lubricant type, elemental carbon black (EC) concentration and size. They concluded that bore polishing is influenced more by the size, nature and concentration of EC rather than by the products of oil degradation. Abrasive wear was not the sole factor contributing to increased wear. Two other phenomena also had an important role to play (1) a decrease of the surface coverage rate by ZDTP molecules due to physical adsorption of soot on the surface (2) a subsequent modification of the physical and mechanical properties of the reaction film by the introduction of carbon in their composition.

Studies on the effect of EGR on engine wear on a heavy-duty diesel engine using analytical ferrography technique were performed by Cadman and Johnson, [33]. Oil samples were collected from the engine sump at specified time intervals through each engine test. The oil samples were analyzed for metal wear debris using analytical ferrography technique. Engine testing with 15% EGR showed a significant increase in the wear particle concentration. Equilibrium particulate concentrations with 15% EGR were ten times higher than normal baseline levels. They suggested that soot acts as an abrasive to remove the anti-wear surface coating by oil additives on the metal surfaces.

Needelman *et al.*, proposed chain reaction of wear theory. At TDC and BDC, there is little or no relative motion of ring and cylinder [34]. At these positions, full lubricant film collapses and mode of lubrication is boundary lubrication. Due to these severe conditions, ring cylinder contact is extremely sensitive to soot contamination. This causes abrasive wear resulting in metal particle generation from the piston and cylinder. These particles were reported to be work hardened particles up to 30 μm in size. These particles act as abrasive to rings, cylinders, and other engine components. When new oil is sprayed on walls of the cylinders, these wear particles are washed into the sump. From a common oil sump, these abrasive particles can circulate throughout the engine and continue the chain-reaction of wear.

To understand the actual state of the soot in the oils, Kawamura *et al.*, conducted the transmission electron microscopy (TEM) observations of soots in oil by the freeze fracture replica (FFR) method. Primary soot particles are 0.02–0.03 μm in diameter, which aggregate and form chain structures [35]. They also suggested that small soot particles up to 0.02 μm in diameter do not affect the anti-wear property. Hence, small aggregates, which are dispersed well in oil, may not behave as pro-wear particles. However, soot particles greater than 0.03 μm may be one of the dominant factors in increased wear.

Trujillo *et al.*, studied various parameters of the lubricating oil affected by EGR and reported that viscosity of the oil increases due to higher levels of soot, oil oxidation due to higher temperatures and nitration by NO_x [36]. The acid number of oil also increases due to acid formation. Effects of EGR are summarized as in table 2.1.

Table 2.1: Effect of EGR

Environmental	Trend	Engine	Trend	Lubricating oil	Trend
NO_x PM emission Fuel efficiency	↓ ↑ ↓	Components Complexity Maintenance	↑ ↑ ↑	Temperature Acids Soot Viscosity Additives	↑ ↑ ↑ ↑ ↑

The engine oils comprise of mainly petroleum base stocks and a set of additives. Existing properties of the mineral base oils are not sufficient to provide an adequate lubricant performance for modern engines; about 10 to 25 percent additives are added [37]. The base oils generally contain paraffinic, naphthenic, and synthetic organic oils. Additives are blended with base stocks to provide desirable properties such as optimum friction, anti-wear and anti-oxidation capability, defoaming capability, and corrosion inhibition etc. The presence of sulfur, phosphorous, alkaline earth metal, zinc, copper, etc. compounds define the composition of additives and the lubricating oils. Nadkarni has summarized the additive elements generally used and their engine performance is given in the Table 2.2 [38].

Table 2.2: Metallic Elements in Lubricating Oils

Elements	Performance
Barium	Detergent inhibitors, corrosion inhibitors
Calcium	Detergent inhibitors, dispersants
Magnissium	Detergent inhibitors
Nickle	Anti-wear agents, carbon deposit reduction
Zinc	Anti-oxidants, corrosion inhibitors, anti-wear additives, detergents, extreme pressure additives

Metals in the lubricating oils come from these additives and also from the mechanical wear from oil wetted components of engine or as a contaminant from air, fuel, and liquid coolant. Generally the metals are present as particulates rather than in solution. The presence of specific metals used in lubricating oils can be associated with specific metal components of an engine. In a normally running engine, wear metal content of the oil slowly increases due to normal wear. However, a sudden rise in one or more metal concentration in oil indicates failure or excessive wear of specific engine

components. Table 2.3 summarizes the typical wear metals its typical source in the engine.

Palus, examined the used motor oil (15W40) by flame AAS and found that the concentration of Zn, Ca and Ba decreases initially of the engine run for few kilometers but after few kilometers of engine run, the concentration of these metals increased [39]. The above metals are present in the lubricating oil as additive and when the engine runs, these additives get consumed.

Table 2.3: Sources of Metals in Lubricating Oil with its Usage

Elements	Source
Aluminum	Piston, Bearing, Dirt
Chromium	Compression rings, coolant, crank shaft. Bearings, plating of cylinder liners
Cobalt	Bearing
Copper	Bearing, piston rings
Iron	Wear from engine block, cylinder liner, rings, crankshaft, anti fiction bearings
Lead	Bearings
Magnesium	Bearings, cylinder liner
Nickel	Piston rings, valves
Zinc	Bearings, platting, brass components

But after few hours, the wear of engine parts increases the concentration of these metals. The concentration of other metals constantly rises as the engine runs. He analyzed metal concentrations in the used lubricating oil for 5000 km engine run at different km runs, as shown in Table 2.4.

2.8 Determination of Metals in Lubricating Oil

Various experimental techniques have been used for metal concentration determination in the lubricating oil, e.g. inductively coupled plasma atomic emission spectroscopy (ICPAES), optical emission spectroscopy (OES), atomic absorption spectrometry (AAS), X-ray fluorescence spectroscopy (XRF) etc. The wear metal studies by these methods are complicated because of high viscosity of lubricating oil and particle size effects. Goncalves *et al.*, reported that AAS is the most common technique for the analysis of metals in the lubricating oils [40]. However, the oil's high organic content and viscosity which makes the determination difficult. They developed an efficient method for determination of metals by emulsion preparation in the lubricating oil. They did a comparative study of metal analysis by treating the lubricating oils using different

methods. e.g. dry ashing, wet ashing, modified wet ashing and the acid treatment. All these methods gave almost same result with some interference in each case.

Table 2.4: Elemental Concentration in 15W/40 Lubricating Oil [39]

Distance (km)	Concentration (µg/g)							
	Zn	Mg	Ca	Ba	Cu	Cd	Fe	Pb
0	2116.50	16.01	5083.86	27.31	0.46	0.15	1.29	2.80
5	1939.14	179.47	3908.20	30.57	5.66	0.76	18.24	424.12
600	1689.50	195.89	3441.66	34.51	21.39	1.13	36.74	792.99
1000	1648.03	198.83	3409.21	35.66	27.01	1.17	37.85	905.24
1500	1626.50	239.80	3399.16	36.87	33.69	1.20	47.70	1076.51
2000	1944.91	307.36	4064.87	37.13	34.65	1.27	87.97	1521.96
3000	1970.66	319.95	4119.99	37.57	34.67	1.28	97.74	1774.83
5000	2011.32	325.12	4131.51	37.88	34.72	1.29	102.85	1798.87

Barbooti *et al.*, determined the metal by following three types of sample preparation. (1) Direct dilution by an organic solvent like xylene (2) Dry ashing acid dissolution (3) Dry ashing in presence of porous silica gel [41]. They got comparable metal concentration from all the methods.

2.9 Soot Loading of the Lubricating Oils

The diesel engine combustion process produces highly carbonaceous material i.e. "soot". Part of this is retained in the engine lubricant (engine soot) and part is expelled into the environment via exhaust (exhaust soot). Engine soot present in used lubricating oils is in aggregated formed, typically consist of about 90% carbon, 4% oxygen, 3% hydrogen, nitrogen, sulfur, and traces of metals [42]. Carbon in used lubricating oil is present mainly in the form of organic carbon. Along with that, few percent of elemental carbon also comes from the soot. The inorganic carbon (carbonates and bicarbonates) are present in negligible amount.

Andrews *et al.*, evaluated lubricating oil of an IDI diesel engine after 120 hrs engine run, and found that carbon contamination of the oil increased to 1.6% by mass [43]. This carbon contamination basically comes from the soot loading of the lubricating oil.

With the view of detailed literature survey it has been found that EGR is an efficient technique for reduction of NO_x formation in diesel engines. But the NO_x and soot trade-off limits the use of EGR. This study was aimed to examine the effect of EGR on engine performance in terms of lubricating oil degradation and wear of vital engine parts.

CHAPTER 3

EXPERIMENTAL SETUP AND METHODOLOGY

To specifically attain the objectives of the study, the experiments (engine run) were conducted in two phases. In the first phase, the engine was run under normal operating conditions (defined later) and in the second phase, the engine was run with a fixed exhaust gas recirculation rate. The engine emissions and performance in the two phases are compared. The emission pattern, smoke opacity, and carbon deposits on various vital parts of the engine were recorded. The wear of cylinder liner and piston rings were also studied. For comparing the wear performance of both sets of engine experiments, samples of lubricating oils were collected after fixed intervals of engine run. The lubricating oil samples were analyzed for presence of heavy metals and soot loading. Major Tasks of the study is shown in figure 1.

3.1 Engine Specifications

A constant speed, two cylinder, four stroke, air cooled, direct injection diesel engine generator set of 9kW rating (Indec PH2 model) was chosen to study the performance of EGR. The specifications of engine are given in Table 3.1.

The engine cylinder liners are air cooled. Cooling of cylinder liners was improved by providing a casing on the flywheel, which forces the atmospheric air around the cylinder liners. The engine is a constant speed compression ignition engine with a fixed rpm of 1500. At 1500 rpm, the engine develops 9 kW power output. The inlet valve opens 4.5 ^{0} before TDC and closes 35.5^0 after BDC. The exhaust valve opens 35.5^0 before BDC and closes 4.5^0 after TDC. The fuel injection release pressure was set to 210 kg/cm^2 @1500 rpm as recommended by the manufacturer. The tappet setting was done after reassembling of the engine in each set of experiments.

Fresh lubricating oil was filled in oil sump before beginning each set of experiment, after engine assembling. The engine is coupled with a single phase, 220 volts AC generator. A load bank of 10 kW with a loading step of 1000 W (1 kW) was used for loading the engine generator system. After completing each phase, engine was dismantled and cleaned thoroughly by draining out all the lubricating oil present in the

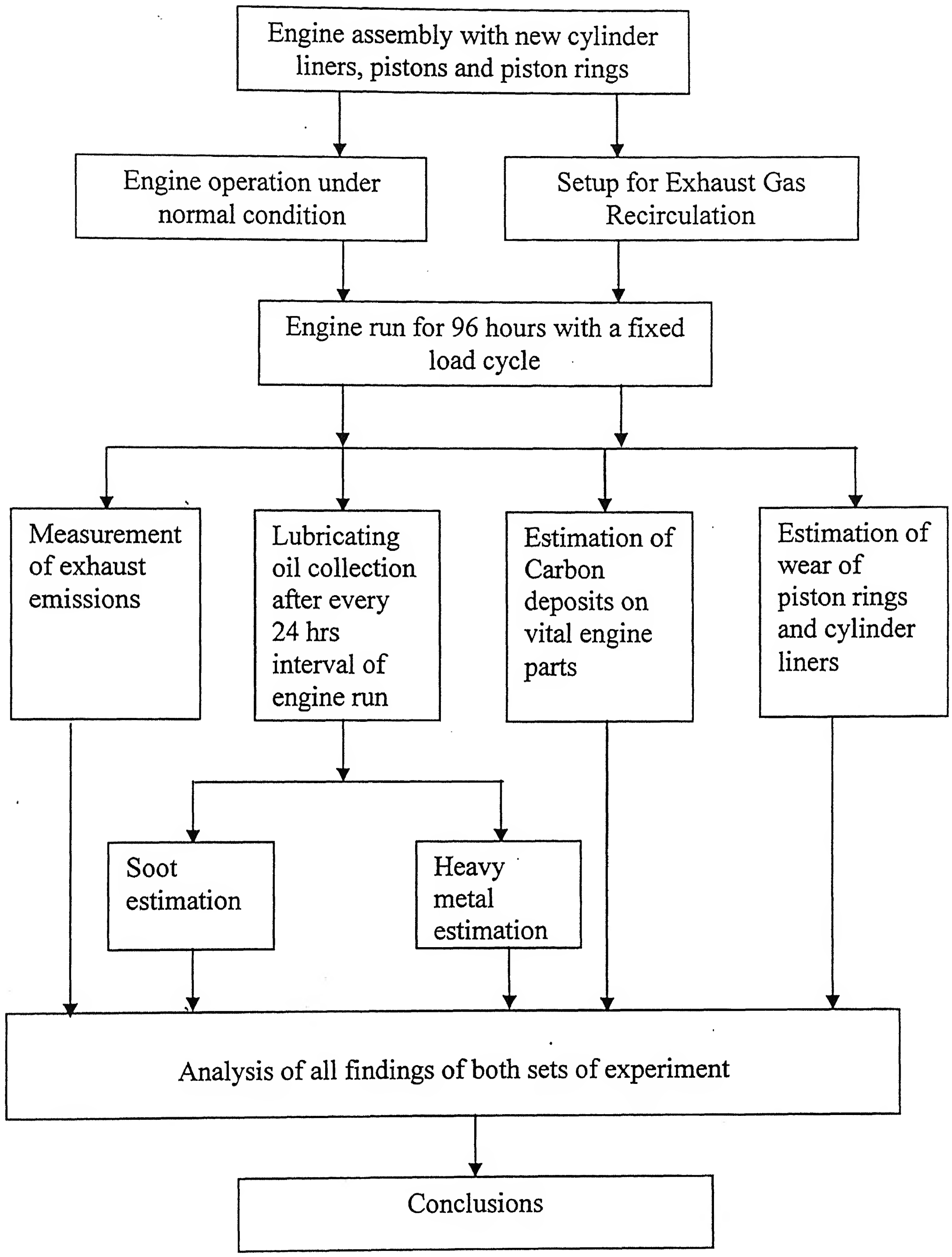


Figure 3.1: Overview of Research work

sump. New set of cylinder liners, pistons and the piston rings were used for reassembly of the engine for next phase. The engine parts were changed as per the instructions/recommendation of the engine manufacturer.

Table 3.1: Engine Specifications

Engines characteristics	Specification
Model	Indec PH_2 Diesel Engine
Injection Type	Direct Injection
Number of Cylinders	Two
Bore Diameter	87.3 mm
Stroke Length	110 mm
Power per Cylinder	6.5 bhp @ 1500 rpm 4.85 kW @ 1500 rpm
Compression Ratio	16.5:1
Displacement	1318 cc
Fuel Injection Timing	24^0 before TDC
Fuel Injection Release Pressure	210 kg/cm^2 @1500 rpm
Oil Sump Capacity	6.8 Liters

3.2 Experimental Setup

In the EGR system, a part of the exhaust gas is recirculated to the combustion chamber after mixing with fresh air. For recirculation of the exhaust gas appropriate piping was done. The schematic diagram of the EGR setup is shown in figure 3.2. The flow path of the recirculating exhaust gas was made as shorter as possible in order to reduce pressure losses. No specific cooling arrangements of the recirculating exhaust gas were made, so the EGR system was short route hot EGR system. The piping was done using GI pipes. Pipes of 1.5 inches (38.10 mm) diameter were used for the inlet and exhaust gas piping. The diameters of these pipes were slightly more than the inlet and exhaust manifold, in order to make the flow of gases smooth. The diameter of pipe used for recirculating loop was 1 inch (25.4 mm). In order to make short route EGR system, the shortest route to the recirculating exhaust stream was provided and the exhaust gases were drawn from exhaust stream immediately after the exhaust manifold.

The exhaust gases from the four-stroke engine come out during exhaust stroke. These exhaust gases come out in highly turbulent form at a high pressure. Measurement of turbulent recirculating exhaust gas flow rate is difficult, so an air box was provided in EGR loop. An air box of approximately 35 liter volume (dimensions 32.5 cms x 32.5 cms x 32.5 cms) was fabricated, with a rubber diaphragm on one side to dampen the

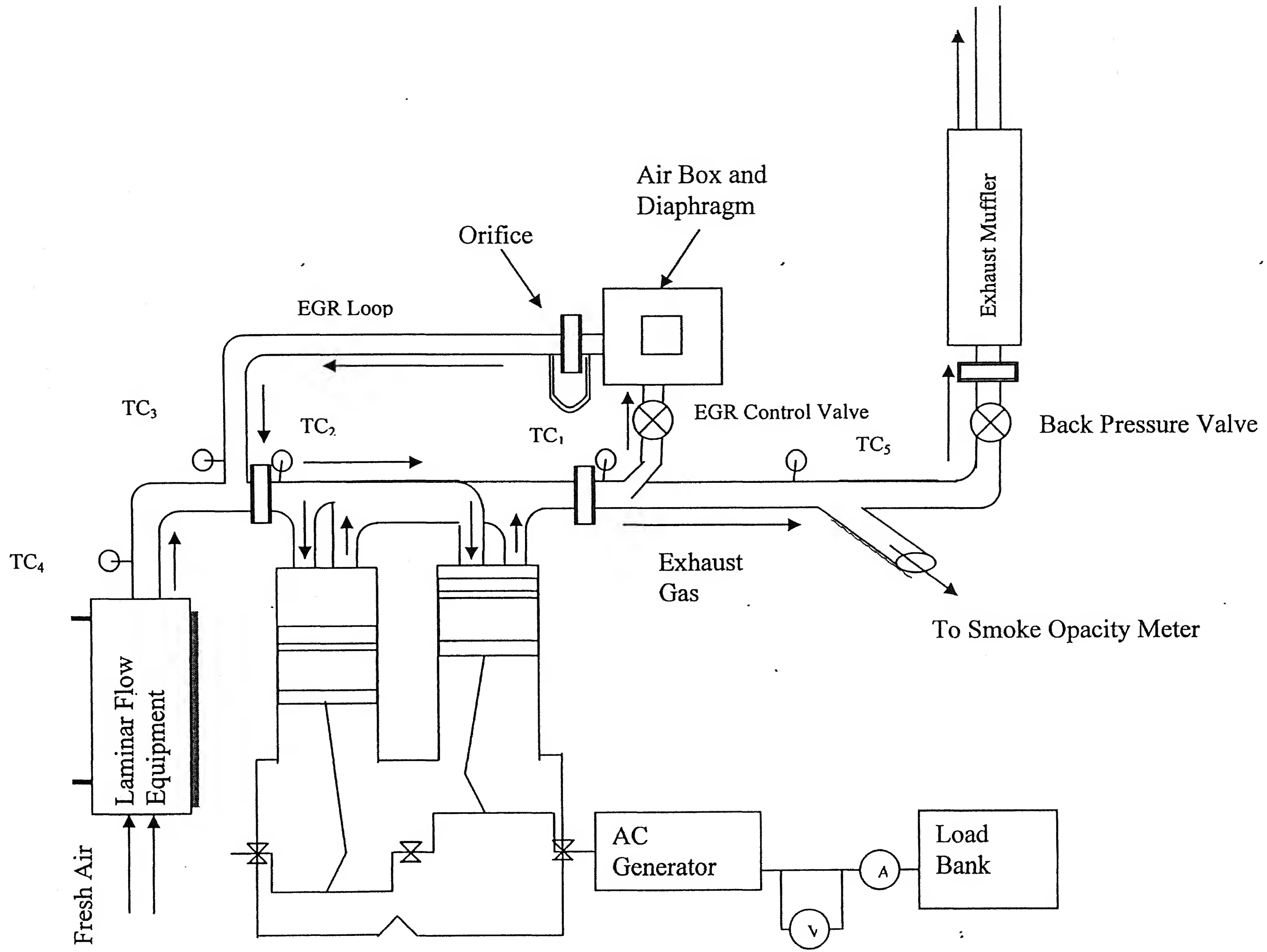


Figure 3.2: Schematic Diagram of Engine Setup Using EGR

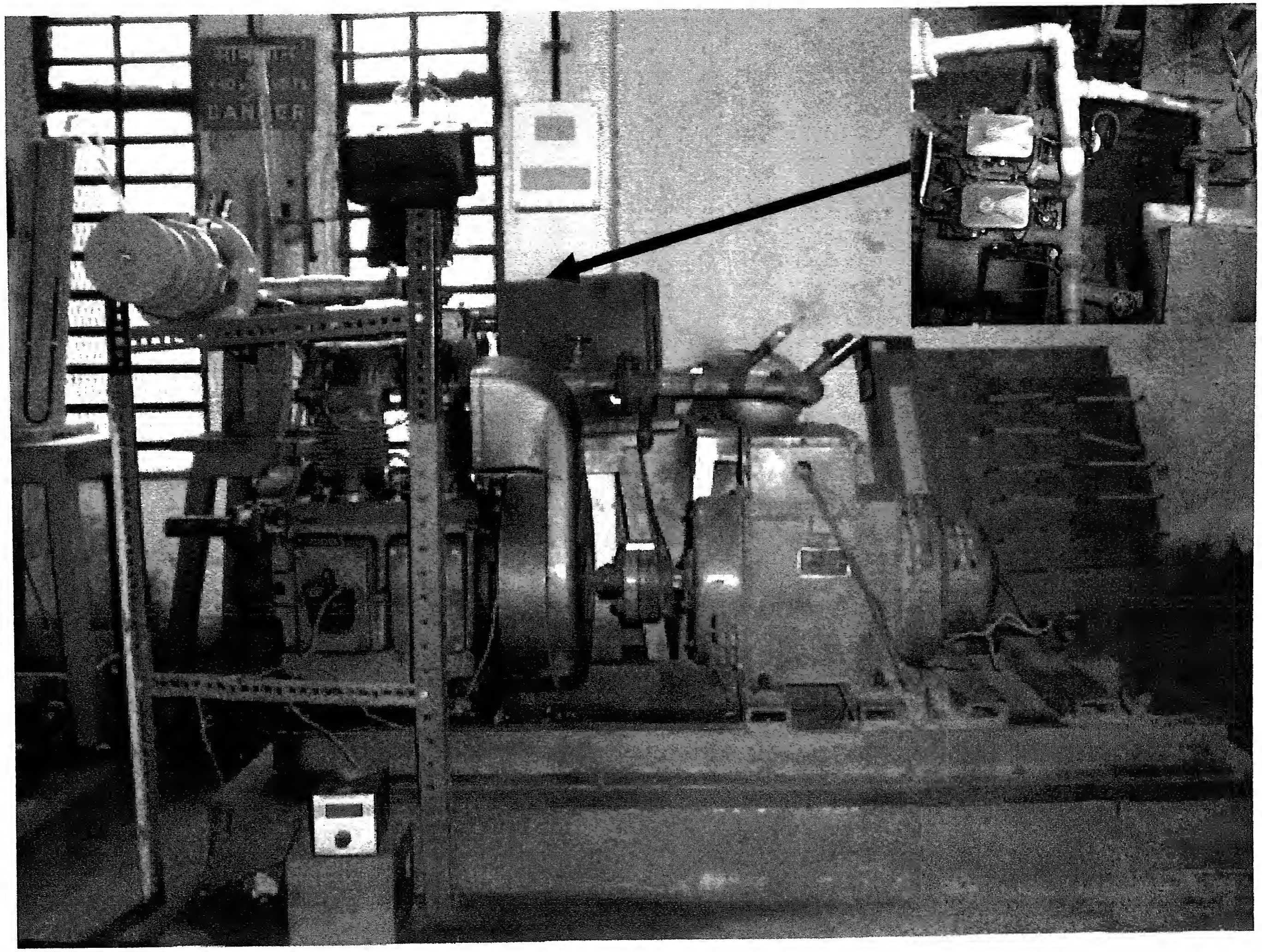


Figure 3.3: Experimental Setup

pressure fluctuation of the exhaust. An orifice was installed in the EGR loop after the air box in order to measure the flow of the gases across it. A U-tube manometer was used for this purpose. The coefficient of discharge (C_d) of the orifice used was 0.62.

In order to achieve high EGR rates, the recirculating line is connected to exhaust line at an angle of 45^0. A backpressure valve is also provided in the exhaust gas line. The quantity of EGR can be regulated by a control valve, which is installed in the EGR loop.

A laminar flow meter (Cussons Make, Model: 7025) was installed for flow measurement of fresh air at the inlet. The air in a four-stroke engine enters only during intake stroke, so the flow of the air in the intake manifold is always pulsating. It is difficult to measure the pulsating flow of air, hence in order to measure the air flow, a laminar flow equipment (LFE) is installed before the intake manifold in the setup. In the Laminar Flow Equipment the air passes through fine fins. When air passes through theses fine fins, air flow becomes laminar. The orifices were installed before and after the fins to quantify the amount of air flow passing through LFE. An inclined tube manometer is installed across the fins of Laminar Flow Equipment in order to measure the flow of fresh air entering the combustion chamber.

Suitable instrumentation for measurement of temperatures at several locations is provided in the experimental setup. Smoke opacity meter (AVL opacimeter) is also installed in the experimental setup.

3.3 Engine Test Matrix

The engine test runs were conducted as prescribed by Emission Test Cycle ISO 8178. ISO 8178 is an international standard designed for non-road engine applications. It is used for emission certification and/or type approval in many countries world wide, including USA, European Union and Japan. The ISO 8178 is basically a collection of many steady state test cycles designed for different classes of engines and equipments. According to ISO 8178, the test run should be conducted in a fix hour cycle of different loading conditions. The cycle should be decided in such a way that the engine runs for 30% of the total cycle time at full load, 50% of the time at ¾ th load and 20% time at half load conditions.

The engine was run with EGR and without EGR (normal operating condition) for total 96 hrs in each phase separately. The test cycle was of 6 hrs. The engine was run at full load, $¾^{th}$ load and half load of the rated power at a constant speed of 1500 rpm. Engine

was run for 16% of the total time at full load, 34% of time at 3/4th load approximately, 34% of time at half load and for approximately 16% of time at no load condition in a 6 hrs run cycle. It may lead to damage or excessive wear of engine parts when high loads are imparted to the engine just after the reassembly with new set of cylinder liners, pistons and rings. Hence in order to avoid any possibility of damage or excessive wear, the engine was run at no load conditions for 12 hrs initially after reassembly the engine. After initial 12 hrs Idling, the test cycle was executed.

Table 3.2: Engine Test Cycle for Endurance Test

Load	Duration (minutes)
No load	20
100% load	30
50% load	120
No load	20
75% load	60
No load	20
100% load	30
75% load	60
Total	360 minutes (6 hrs)

Literature review suggests that 20-30% EGR leads to significant reduction in NO_X with lower penalties in PM emissions and break specific fuel consumption. In normal operating condition, no recirculation of the exhaust gas was allowed.

3.4 Exhaust Gas Analysis

The smoke opacity, soot density and the temperature of exhaust was measured to quantify the exhaust emission. The opacity of the exhaust was measured by AVL Smoke opacity meter. The opacity is defined as the extinction of light between the light source and receiver. The smoke opacity is measured to quantify the amount of particulate matter present in the engine exhaust.

AVL 437 smoke opacimeter was used for measuring smoke opacity. In the opacity meter, the exhaust smoke is a chamber having non-reflective inner surfaces. The light is passed through this chamber. The light source is an incandescent bulb with a temperature between 2800 K and 3250 K. The light travelled through the chamber and falls on a photocell placed at the other end of chamber. The current delivered by the photocell is a linear function of the intensity received by it. When the light is passed through the chamber with exhaust smoke, the particulate matters present in the smoke,

hinders the path of light. Thus only a fraction of light reaches to the photoelectric cell, which gives a voltage signal. The voltage signal is reciprocal to the opacity of the exhaust smoke.

For measuring the opacity of the exhaust gas AVL 437 SMOKE METER was used. The equipment is being used to check and approve emissions of auto-ignition combustion engines and measures the opacity and light absorption of the smoke. The AVL 437 smoke meter measures the opacity of the polluted air, in particular diesel exhaust gases (in a measurement chamber of a defined measurement length). The effective length of the measurement chamber was 0.430 ± 0.005 m. The temperature of the exhaust gas to be measured was kept between 70°C and 130°C as per recommended by the manufacturer.

The care was Taken in the sampling of the exhaust gas as per recommended by the manufacturer of the instrument. The ratio of the cross section of the probe to the cross section of the exhaust pipe was 1.27. The ratio of the cross section of the probe to the cross section of the exhaust pipe must be at least 0.05, as per recommended by manufacturer.

3.4.1. Soot Density

The soot density in the exhaust gas was calculated by Smoke Density Calculator. This calculator computes diesel soot density from smoke opacity.

The input parameters for calculating smoke density are;

- Smoke Opacity (%)
- Light path length (cm)
- Temperature (°C)

The out puts parameters from the algorithm are;

- Light extinction coefficient (1/cm)
- Soot density (mg/m^3)
- Soot density @ STP (mg/Nm^3)
- Mass fraction of soot (mg/kg)

3.5 Collection of Lubricating Oil Samples

SAE 20W/40 grade lubricating oil was used for lubricating the engine run. The lubricating oil from the same container was used in both set of engine test run in order to avoid any possibility of changes in additives/heavy metal contents of the lubricating

oil. Lubricating oil was filled to the desired level of oil sump. To analyze the exact amount of heavy metals addition in the lubricating oil in order to quantify the engine wear during test run, no further addition or make up of lubricating oil was done in complete test execution of 96 hrs.

Lubricating oil sample of 100 mL was drawn in plastic bottle from the drain hole, after every 24 hrs of engine run for heavy metal and soot loading analysis. The lubricating oil samples were drained out carefully according to standard sampling procedures from the engine in order to minimize the losses of lubricating oil. After collection of samples, they were kept air tight and stored at room temperature. The analysis for heavy metal and soot loading of the lubricating oil was done soon after collection of all the samples in each phase of test run.

3.6 Estimation of Heavy Metals in Lubricating Oil

Keeping in view the objective of the research of analyzing the degradation of lubricating oil with the usage of the engine, addition of wear metals were analyzed in lubricating oil samples. The analysis was done for both sets of test run i.e. with EGR and without EGR. The predominant heavy metals addition in the lubricating oil due to engine parts wear are Al, Fe, Zn, Ca, Cu, Cr, and Ni. There are various sources of these metals in the engine from which they come to lubricating oil such as wear of piston, rings, cylinder liner, bearings, gears and other vital engine parts. Along with these some metals are added to the lubricating oil as additives in order to enhance the properties of lubricant base stock.

In the present work, metals which are present in large quantity in lubricating oil were analyzed along with metals, which are present in tracer amounts. The heavy metal analysis was done for Fe, Ca, Mg, Cr, Ni, Zn, Pb, Cu, Mn, and Al, in order to study the effect of EGR on wear of various engine parts. The analytical technique used for quantification of heavy metals was AAS.

3.6.1 Atomic Absorption Spectroscopy for Lubricating Oil Analysis

The analysis of heavy metals in the lubricating oil has always been difficult due to its high viscosity and non-homogeneous particle size distribution. For analyzing the heavy metals content in the lubricating oil, its viscosity needs to be decreased. The extraction of metals from the complex organic compounds of the oil was also desirable. For maximum possible extraction of metals from the lubricating oil samples, they were

made homogeneous by shaking them vigorously and then putting them in a water bath at a temperature of 50°C for 1 hour.

The heavy metal concentrations were determined by Flame Atomic Absorption Spectrophotometer (using the instrument Varian AAS spectra AA 220FS).

For extraction of heavy metals from the lubricating oil, dry ashing technique was used. The procedure adopted for extraction of heavy metals is as follows.

a) Approximately 5 gm of homogenized lubricating oil samples were weighed in previously washed and dried silica crucibles. The crucibles were then kept on a hot plate at a temperature of 120°C till the lubricating oil gets completely dried up.
b) The crucibles were then kept in muffle furnace at a temperature of 450°C for 4 hours and then at 650°C for 2 hours.
c) The ash remained in the crucibles was then dissolved in 1.5 mL concentrated HCl.
d) The solutions were then diluted to 100 mL by de-ionized water and stored in plastic bottles and kept in a in refrigerator at a temperature of 10 - 15°C.

The diluted samples were then analyzed on flame AAS. Calibration graphs were prepared by using standard metal solutions in the linear range of optical density. The lower and upper concentration of standard metal solutions were prepared keeping in view the optimum working range of each heavy metal, recommended by the manufacturer of the instrument.

The standard solutions were freshly prepared at the time of analysis and the samples were diluted according to the working range of instrument. In order to ensure the consistency and maximum possible extraction of heavy metals from the lubricating oil samples, all the crucibles and glass wares were subjected to acid wash and drying in order to avoid any contamination from previous samples. The samples were digested in duplicate to check the repeatability of the experimental data.

3.7 Soot Loading in Lubricating oil

The lubricating oils from the engines contain negligible amount of carbon in inorganic form. Base stock of lubricating oils is basically organic compounds and additives are complex organic compounds of metals. The additives are added in the base stock of the lubricating oil to enhance the properties of lubricating oil. There are very little chances of reaction of the lubricating oil in order to form carbon in inorganic form at the time of

engine run. Keeping these points in mind, the lubricating oil samples were analyzed for total carbon (TC). The change in the amount of carbon present in the used oil from the fresh oil is assumed to be a reasonable approximation of soot loading of lubricating oil as a function of its use. The lubricating oil was analyzed separately for inorganic carbon also.

For total carbon analysis the lubricating oil samples were analyzed on the Total Organic Carbon Analyzer (Shimadzu make, Model: TOC-V CPN). The total carbon in the samples was analyzed in the TC furnace of the instrument. Approximately 25 mg of lubricating oil samples were weighed on previously cleaned boats and placed in TC furnace. The TC furnace was maintained at 900° C to convert total carbon in to CO_2. In order to facilitate complete conversion of carbon in to CO_2, platinum catalyst was provided in the furnace. The CO_2 thus generated in the furnace was measured in the IR detector chamber. The TC was analyzed in duplicate. The samples were also tested for inorganic carbon (IC) by putting the boats in the furnace for IC analysis. The temperature of the IC furnace was maintained at 200°C and excess amount of phosphoric acid was added to convert all the inorganic carbon to CO_2.

3.8 Estimation of Soot Deposits on Engine Parts

A qualitative analysis of the soot deposits on various vital engine parts was done photographically. Digital photographs of the various in-cylinder engine parts were taken in order to make a comparison of soot formation. Photographs of cylinder head, piston crown, and injector tip were taken for both engine run. These parts of engine are exposed to the combustion. The photographs were taken by Sony Digital camera.

3.9 Estimation of Wear

Piston rings and the cylinder liners are exposed to high temperature due to combustion. This high temperature and motion of piston during engine run causes wear of the piston rings and cylinder liners.

3.9.1 Piston Rings

Piston is one of the main components, which is subjected to enormous thrust by burning gases and piston transmits this thrust to the crankshaft. The piston has to withstand high temperatures and pressures in the power stroke of engine cycle. Taking all these facts in to consideration, pistons are made of very strong material so that they can withstand the load and temperature and are machined accurately in order to achieve

good sealing in all conditions when engine is cold and running hot as well. All the pistons used in a multicylinder engine are balanced i.e. all the pistons have equal weights. The piston carries piston rings, which are used to seal the combustion chamber from the sump. Piston rings are used to maintain gas tight seal between combustion chamber and crank case, to assist in piston cooling and to control cylinder wall lubrication. Piston rings must be able to withstand high pressure with high durability. They should absorb minimum amount of power in order to over come frictional losses. Two types of piston rings are being used in an engine.

1) Compression rings
2) Oil control ring

In this experimental setup three compression rings are used. During compression and power stroke, the compression ring seals the air and burning charge respectively and maintains compression pressure and prevent blow by of combustion gases in to the crankcase. At the same time, during exhaust stroke they seal the passage so that exhaust gases do not enter in to the crankcase and are pushed out of the cylinder through exhaust manifold.

The main purpose of the oil ring is to scrap excess oil from the liner surface and push it back to the oil sump. Generally one oil ring is used in a cylinder. The pressure of the oil ring against the cylinder wall should not be too high to scrap it dry, however it should

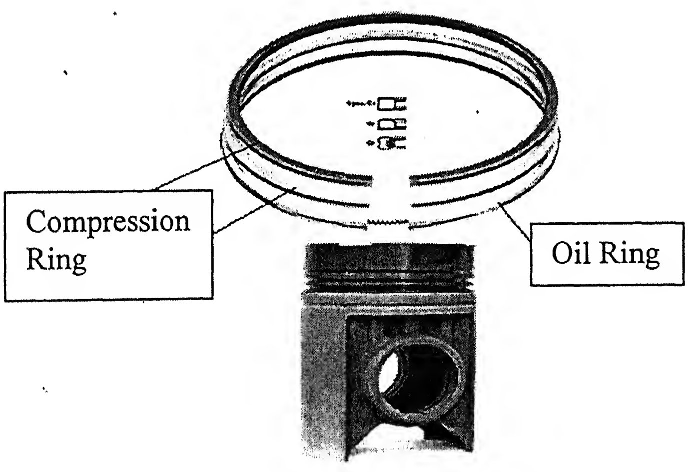


Figure 3.4: Piston and Piston Rings

allow a thin film of lubricating oil to stay on liner surface for sealing and for avoiding metal-to-metal contact. For the piston rings, preferred base material is cast iron and chromium is the most widely used coating material. Cast iron has reasonable

mechanical strength especially compressive strength. It has good bearing and wear resistant qualities, corrosion resistance and damping capacity. Plated chromium on the ring periphery provide best compromise of scuff, wear and corrosion resistance coupled with low friction and oxidation resistance at high temperatures.

In present experiments, piston rings were weighed before and after 96 hrs of the engine test run for both set of experiments, to compare the piston ring wear (on the basis of loss in weights of the rings). To avoid any foreign material stuck in the rings they were cleaned properly. The rings were weighed in a balance having least count of 0.1 mg.

3.9.2 Cylinder Liners

Cylinder liners are hollow cylindrical metallic tubes, generally made integral or fixed in cylinder blocks. In this test engine, the cylinder liners from a link between crank case and the cylinder head of the engine. The cylinder liner walls are stressed by high combustion gas pressure and side thrust of the piston, and these are also thermally stressed due to high combustion gas temperatures. Since all these stress induced factors are cyclic in nature, the cylinder liner material must have good mechanical and fatigue strength, otherwise cylinder bore distortion or early material fatigue failure may take place. In addition, the tribological properties such as wear and scuff resistance must also be satisfactory because metal to metal contact between the piston rings and the cylinder liner do occur.

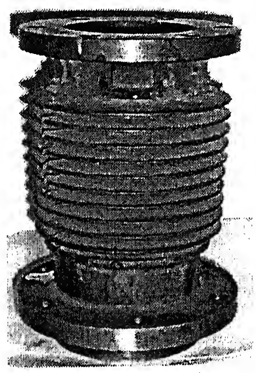


Figure 3.5: Cylinder Liner

Most cylinder liners are made up of gray cast iron. To increase the mechanical strength of the material addition of nickel, chromium, copper and molybdenum are required.

The major causes of the wear of cylinder liner are piston side thrust, pressure of piston rings, heat, abrasive action of dust and soot, and less lubrication of liner surface. In both sets of experiments, new cylinder liners were used. To check the wear of cylinder liner material during the course of engine test run, surface profiles of the surface were

taken, before and after 96 hrs of engine test run. The surface profiles were taken at three locations, top dead center (TDC, 14 mm below from top of cylinder liner), mid stroke (60 mm below from top of the cylinder liner) and at bottom dead center (BDC, 124 mm below from top of the cylinder liner) on thrust and on anti thrust side. TDC and BDC are the most important locations of the cylinder liner where maximum wear takes place. The surface profiles were taken on thrust and anti thrust side. The piston skirt touches the liner surface in intake stroke to the thrust side and for the rest of the three strokes it touches the anti thrust side. So these sides are chosen to study the wear of the cylinder liner material.

The surface profiles of the cylinder liner were done by Mitutoyo SJ 301, Surface Roughness Tester. The SJ 301 evaluates the surface textures with a variety of parameters such as R_a, R_q, R_v, R_t etc. In this instrument, the stylus traces the minute irregularities of the liner surface. Surface roughness is determined from the vertical stylus displacement produced during the detector traverse over the surface irregularities. Before taking the surface profiles the instrument was calibrated with the help of standard surface work piece provided with the instrument. R profile was taken for each surface profile and roughness parameters were measured. The roughness parameters have been discussed in Appendix-C.

CHAPTER 4

RESULTS AND DISCUSSIONS

Based on the objectives of the study a detailed plan was prepared for conducting the experiments. The engine was run on a fixed engine loading cycle (as described in chapter 3) for 96 hours in two phases. In the first phase of the experiments, the engine was run with the same load cycle for 96 hours under normal operating conditions (Without EGR). In the second phase of experiments EGR setup was installed on the engine and the engine was run using the same loading cycle at fixed EGR rate of 25%. In order to achieve objectives of this study, various analyses were done in both phase of experiments. The analyses were done at the time of experiments as well as after the completion of the experiments.

This Chapter presents summary of the experimental data, analyses of results and interpretation of the results. The results of this study are summarized in following sections.

1. Engine exhaust measurements and analyses
2. Analysis of lubricating oil for heavy metal and soot loading
3. Effect of EGR on wear of rings and cylinder liners

4.1. Characterization of Emissions

The major concern of study was to reduce the emissions and toxicity from diesel engines. The major pollutants from diesel engines are NO_x and PM. The NO_x and PM emissions are indirectly measured in the experiments using exhaust gas temperature and smoke opacity.

4.1.1 Estimation of Exhaust Gas Temperature

It has been observed that NO_x formation is a highly temperature dependent phenomenon and extremely high temperatures (above 2000 K) of the combustion chamber causes the formation of NO_x, which comes out in the engine exhaust. Decrease in exhaust temperature because of variation of some parameters is a safe indication of the reduction in the formation of NO_x [44].

The temperature of the exhaust gas recorded in both phases of experiments just after the exhaust manifold of the engine.

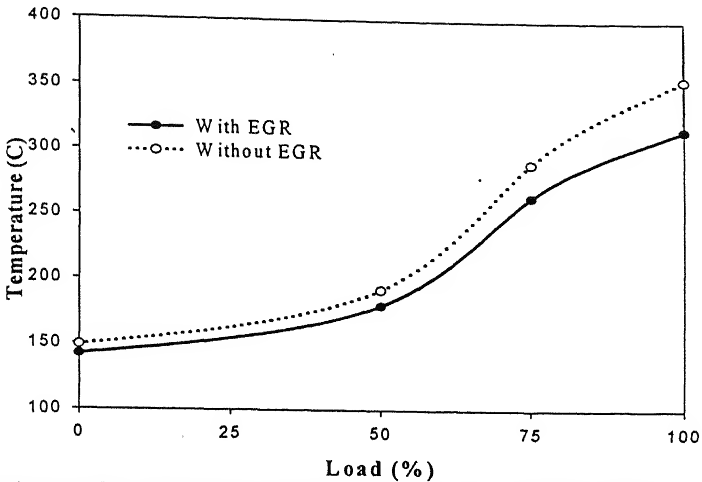


Figure 4.1: Exhaust Gas Temperatures for Engine Operating with and without EGR

The temperature profile is shown in figure 4.1. It has been observed that in both phases of experiments as the load has been increased the temperature of the exhaust gas increases. When the engine is operated in the recirculating exhaust gas condition the temperature of the exhaust gas is always lower than the temperature of the exhaust gas of normal operating condition.

It is observed from figure 4.1 that at high engine loads exhaust gas temperature reduction was higher for EGR condition. The possible reason for this temperature reduction in the EGR system may be insufficient availability of oxygen for proper combustion at high loads i.e. at lower A/F ratio.

4.1.2 Estimation of Smoke Opacity

The smoke opacity of the exhaust gas is measured to quantify the particulate matter present in the exhaust gas. Opacity is defined as the ability of the exhaust gas to block the light. When the exhaust containing particulates is passed through the detection chamber of smoke opacimeter, the particulates block the path of light.

The amount of light reaching the photo detector placed at the rear end of the exhaust gas tube is used to quantify the particulate matters in the exhaust gas. Due to nucleation of unburnt hydrocarbons and condensation of water vapor, the formation of particulate matters takes place. The smoke opacity of the exhaust gas was recorded for both phases of experiments. As the load increases, smoke opacity also increases. High smoke opacity of the exhaust was observed when the engine was operated with EGR condition without EGR condition. The smoke opacity profile is shown in figure 4.2.

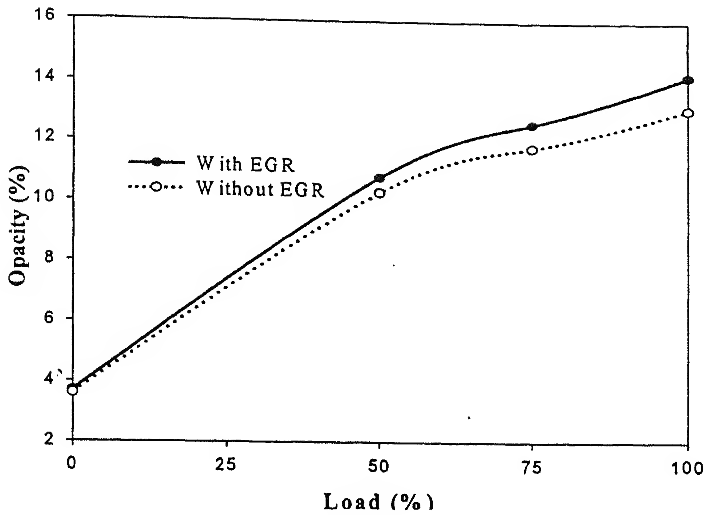


Figure 4.2: Smoke Opacity for Engine Operating with and without EGR

The variation in smoke opacity level at high loads was higher compared to that at lower loads. When the engine was operated with EGR, availability of oxygen for combustion of fuel gets reduced. This increases the possibility of complete combustion in the combustion chamber and increases the formation and release of particulate matter in the exhaust. The soot density was calculated using Smoke Density Calculator with the input of smoke opacity. The variation of soot density is shown in figure 4.3. The soot density of the exhaust coming out of for the engine operated with EGR is higher than the engine under normal operating condition (without EGR).

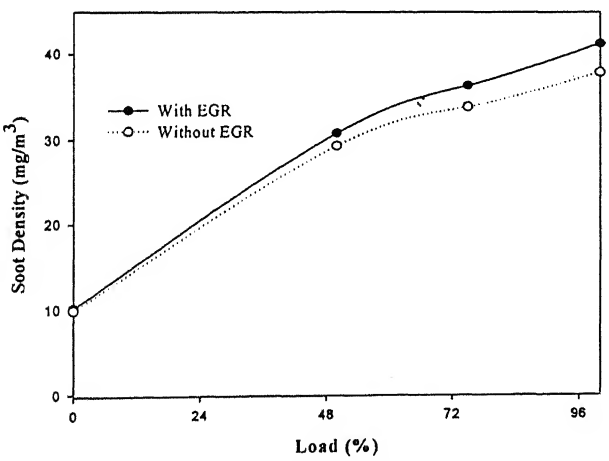


Figure 4.3: Soot Density for Engine Operating with and without EGR

It has been observed from figure 4.1 and 4.3 that when the engine is operated with recirculating exhaust gas, temperature of the exhaust gets decreases and soot density increases with respect to engine operated in without EGR condition. The relative fall in

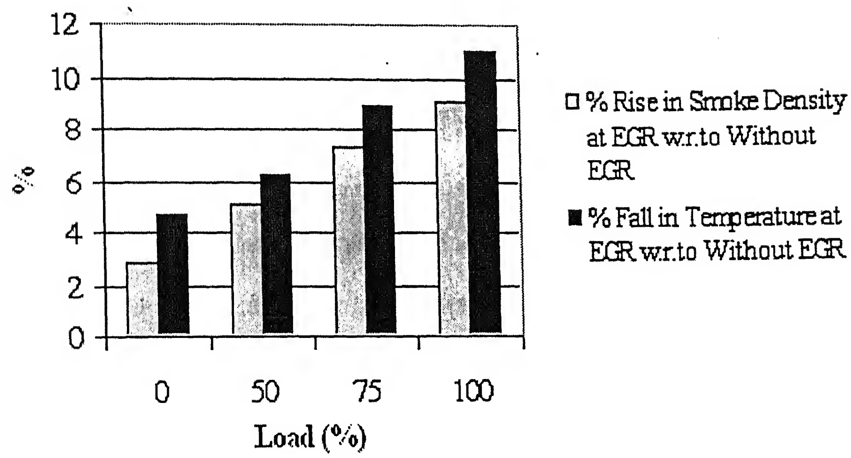


Figure 4.4: Comparison of Smoke Density and Temperature of Exhaust

temperature and rise in soot density of exhaust of the engine operated in EGR condition with respect to that of the engine operated in without EGR condition is shown in figure 4.4.

The relative fall of temperature is more dominant at higher load operating conditions. The soot density of the exhaust is also considerably high.

These results reflect that using EGR leads to substantial reduction in exhaust gas temperature (or in other words NO_x formation), however the soot formation increases. The problem of soot can be controlled easily by exhaust after treatment i.e. by using suitable particulate traps.

4.2. Characterization of Lubricating Oil Samples

The lubricating oil is made of base oils, which are petroleum products along with a set of additives. The properties of base stocks are not enough to provide adequate lubricating oil performance, so additives (up to 10-25%volume of oil) are added to the base stock, which enhances the lubricating oil properties. These additives are complex organo-metallic compounds. When the engine run take place, the relative motion of engine parts leads to generation of wear debris and these wear particles are washed away by the lubricating oil to the oil sump. Hence, the elemental analysis of the lubricating oil gives a fair idea of wear of vital engine parts. The disposal of used engine oils is a big environmental challenge because they contain traces of heavy metal contained in wear debris. The wear debris originates from different parts, and may have different metallic composition depending on the originating parts.

4.2.1 Elemental Analysis of the Lubricating Oil

Various elements, which can be detected as wear debris from lubricating oil drawn from engine operating with and without EGR at regular intervals include Fe, Cu, Cr, Al, Ni, Zn, Mg, Pb, Ca, Mn etc. The lubricating oil samples are drawn from the oil sump following standard sampling procedures at a regular interval of 24 hours for both phases of experiments. The results of the metal analysis are discussed in this section.

Iron: The iron in the lubricating oil may originate from cylinder liners, pistons, gears, rings, cam shaft, oil pump, crank shaft, bearings, etc. The results of the concentration of iron as a function of oil usages in both phases of experiments are shown in figure 4.5. It has been observed that during initial running of engine, the iron concentration rises at a fast rate and followed by slow and steady rise. The reason for this behavior is running in. A new set of liners are installed in the engine, which wear out faster initially as it contains high peaks on the honed surface. When the engine starts running, there is a relative motion of piston rings and liners. The rings start rubbing on the surface of liners in the event of insufficient lubrication or lubricating film breakdown and metal to metal to contact results in wearing out of the peaks on the liner surface.

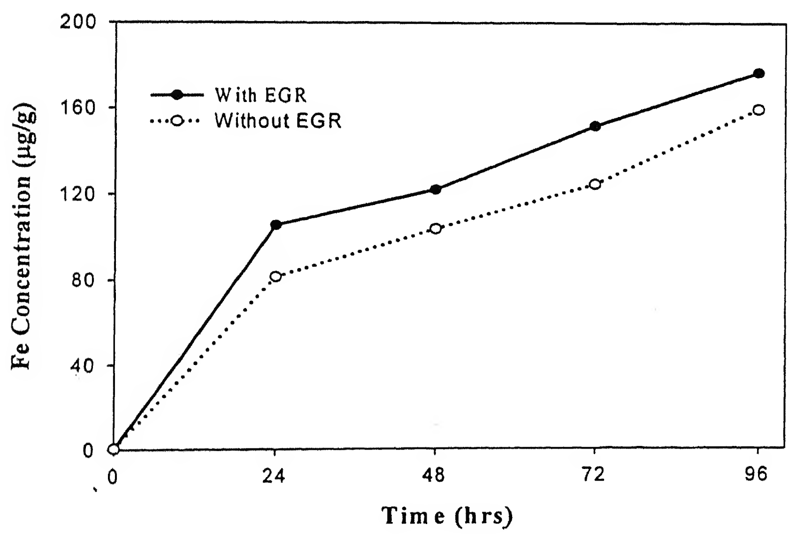


Figure 4.5: Fe Concentration as a Function of Lubricating Oil Usage

After initial phase of engine run, the rate of increase in iron concentration in the lubricating oil reduced and stabilized for the entire test run. This indicates the uniform rate of wear of engine parts in the later phase of engine operation for both cases of EGR and without EGR.

The most important observation from figure 4.5 is that the concentration of iron was found to be more while using EGR compared to engine operating without EGR. High amount of soot particles are generated in the engine operated with EGR. When the soot particles stick with the film of lubricating oil, a three body wear takes place between the surface of rings and liner. The amount of iron concentration was 8 -10% higher in the lubricating oil of EGR operated engine. One of the possible reasons for higher Fe concentration in lubricating oil may be the higher soot loading of lubricating oil, which reduces the lubricating efficiency of oil and at the same time, the soot particles acts as abrasives.

Copper: The copper in the wear debris originates from bushings, injector shields, valve guides, connecting rods, piston rings, bearings, bearing cages etc. The results on concentration of copper as a function of oil usage are shown in figure 4.6. It has been observed that for both phases of experiments copper concentration rise with almost a constant rate. For initial 24 hours of engine run the rate of rise in concentration of copper was slightly higher in both the systems. The concentration in lubricating oil is approximately 5-7% higher in engine operating with EGR.

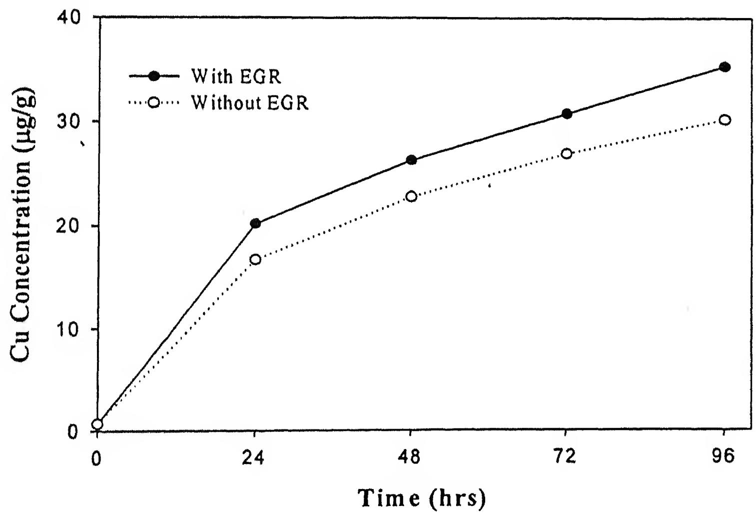


Figure 4.6: Cu Concentration as a Function of Lubricating Oil Usage

Chromium: Chromium in the lubricating oil comes from the wear of cylinder liner, compression rings, gears, crank shaft, bearings etc. The results on concentration of chromium as a function of oil usage are shown in figure 4.7.

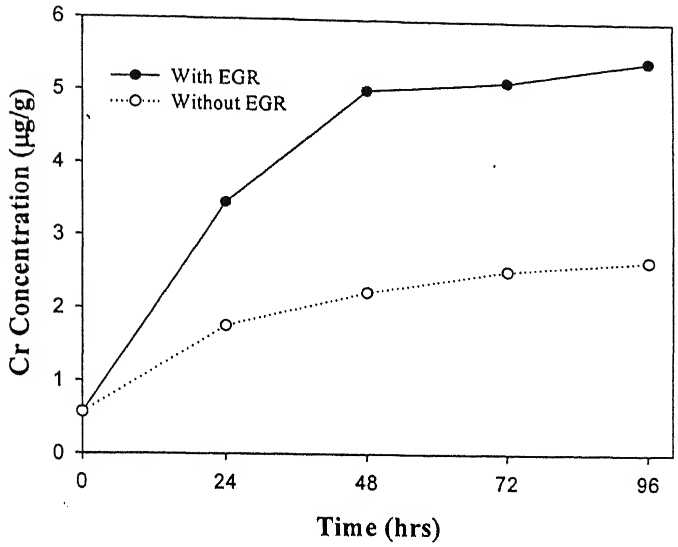


Figure 4.7: Cr Concentration as a Function of Lubricating Oil Usage

Very small amount of chromium was found in the lubricating oils for both phases of experiments and the rate of rise in level of chromium concentration were almost similar thorough out the experiments. The amount of chromium in the lubricating oil from the using EGR system was found to be more than normal that of engine operating without EGR.

Nickel: The organo-metallic additives having nickel are added in very small quantity to the lubricating oil as an additive as an anti wear agent. Hence nickel was found in the fresh lubricating oil in a very smaller quantity.

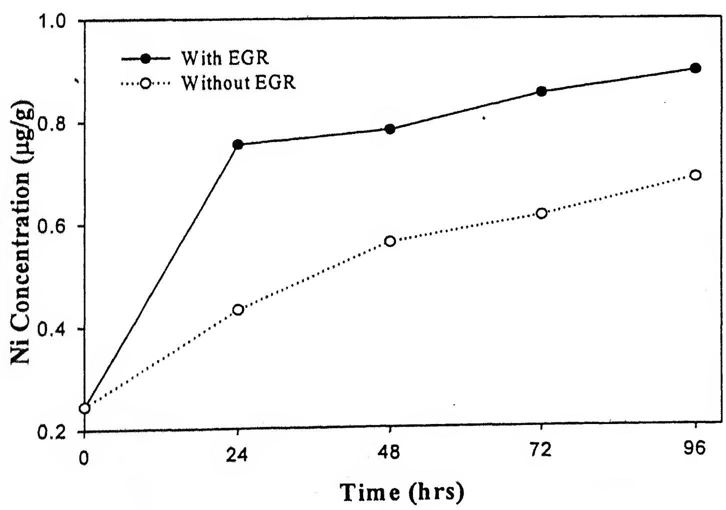


Figure 4.8: Ni Concentration as a Function of Lubricating Oil Usage

The results on concentration of nickel are shown in the figure 4.8. Nickel also originates from bearings, valves, gear plating etc. The nickel concentration rises at a faster rate for initial 24 hours of running of both the systems and after 24 hours, the rate of rise stabilizes.

Aluminum: Aluminum comes originates from piston, bearings, push rods, oil pump, gears etc. The concentrations of aluminum in the lubricating oil as function of oil usage are shown in figure 4.9. It has been observed that the concentration of aluminum is higher in the lubricating oil drawn from engine using EGR system. The rate of rise of aluminum concentration in the normal operated engine is almost constant throughout the experiment, however this rate is higher for initial 48 hours for engine using EGR.

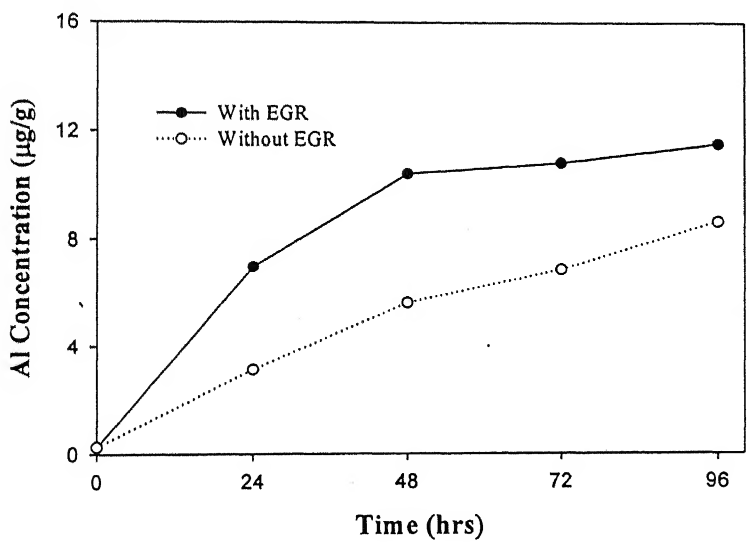


Figure 4.9: Al Concentration as a Function of Lubricating Oil Usage

Manganese: Manganese was found to be in very smaller quantity in the lubricating oil even after 96 hours of engine run. Manganese comes in the lubricating oil due to wear of cylinder liner, valves, shafts etc. The variation of manganese in the lubricating oil as a function of oil usages is shown in figure 4.10. For initial 24 hours of engine run the manganese concentration rises at a faster rate. After 24 hours of engine run, the rate of rise stabilizes.

Lead: The concentration of lead as a function of lubricating oil usage is shown in figure 4.11. The organic complexes of lead are added in the lubricating oil as extreme

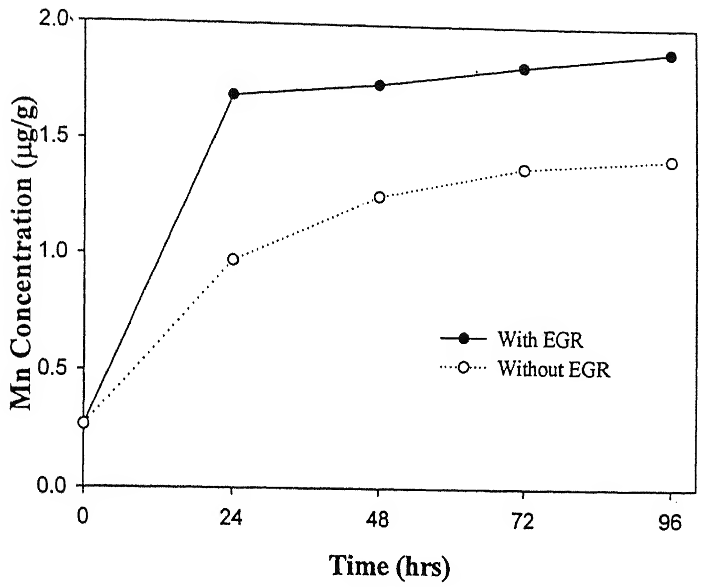


Figure 4.10: Mn Concentration as a Function of Lubricating Oil Usage

pressure additive. It is detected in used lubricating oil because of additions due to wear of bearings and fuel blow-by.

Magnesium: The variation of magnesium concentration in the lubricating oil with usage is shown in figure 4.12. The magnesium is added to the lubricating oil as detergent inhibiter additive. Wear of cylinder liner surface and gears causes magnesium loading to the lubricating oil. It was found that the magnesium loading was 18-20% higher in the lubricating oil from the engine using EGR system than one without EGR.

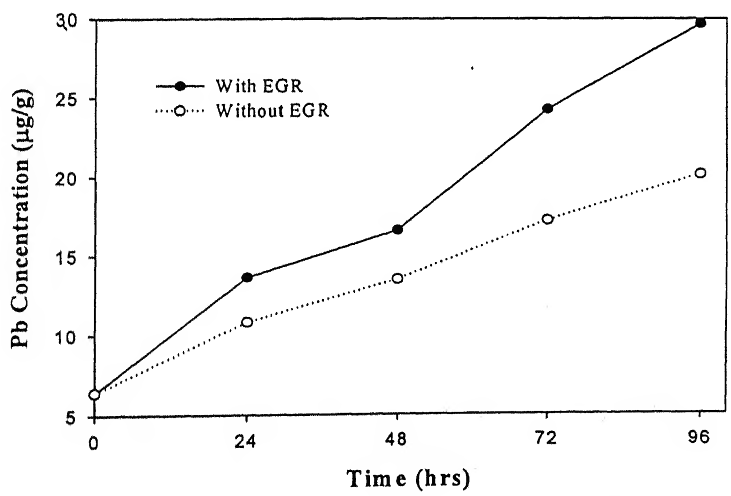


Figure 4.11: Pb Concentration as a Function of Lubricating Oil Usage

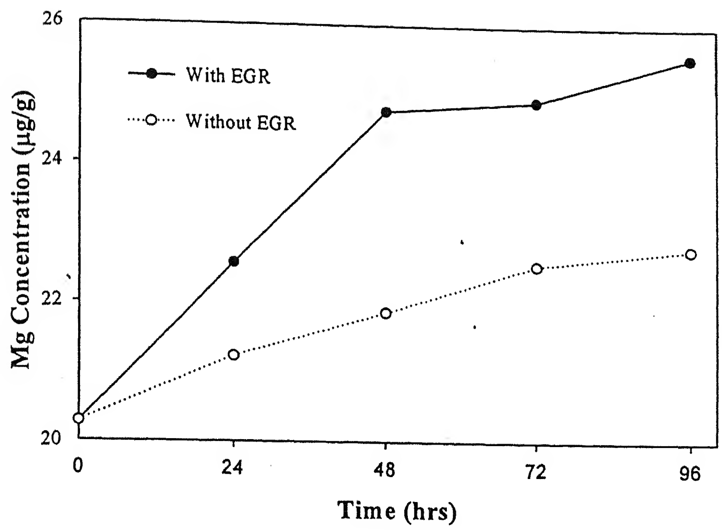


Figure 4.12: Mg Concentration as a Function of Lubricating Oil Usage

The concentration of all heavy metals such as Fe, Cu, Cr, Al, Ni, Mn, Pb and Mg was found to be increasing in both phases of experiments. In the initial engine run, the concentration of these metals rises at faster rate. Due to initial engine running is leading to insufficient lubrication because of rough surface of new engine parts. After initial running in, wear rate decreases because the rubbing surfaces get smoothened. Agarwal *et al.*, have shown a similar trend of wear metals in the used lubricating oils from diesel and bio diesel operated engines [45]. Palus has also found higher rate of wear for initial running of the engine [39].

Zinc: Concentration of zinc as a function of lubricating oil usage is shown in figure 4.13. Zinc is added in the form of ZDTP to the lubricating oil as multi functional additive such as antioxidant, corrosion inhibitor, antiwear additive, detergents, and extreme pressure additive. Hence, fresh lubricating oil contains a reasonable amount of zinc as organo-metallic complex. The initial amount of zinc in the lubricating oil was detected to be approximately 570µg/g. Wear of galvanized piping, and addition of makeup oil are the main sources of zinc in the used lubricating oil.

Figure 4.13 shows that concentration of zinc in the lubricating oil gets reduced during initial hours of engine running, for both set of experiments. After initial 24 hours of engine run the concentration of zinc in the lubricating oil was found to be rising. The reduction in the zinc concentration for the initial hours may be because of evaporation of zinc containing species from the lubricating oil due to initial thermal stressing of the

oil. After initial engine run, zinc gets added to lubricating oil due to wear of various moving parts which increase the concentration of zinc in lubricating oil.

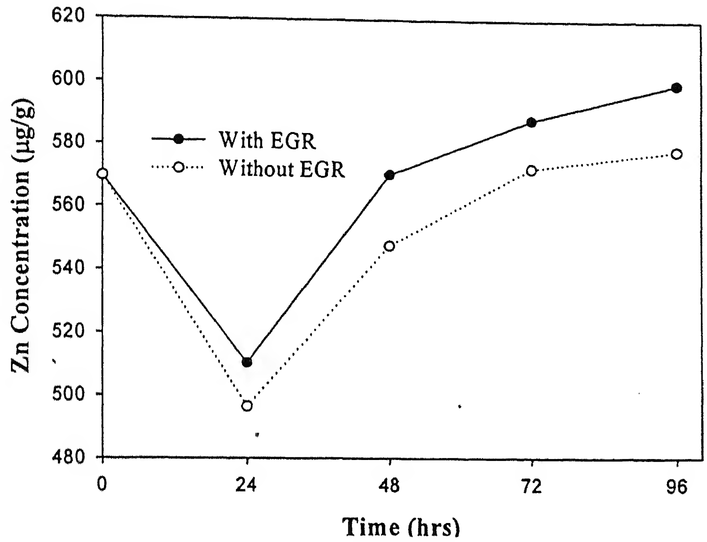


Figure 4.13: Zn Concentration as a Function of Lubricating Oil Usage

Calcium: Figure 4.14 shows calcium concentration of lubricating oil as function of lubricating oil usage. It has been observed that calcium concentration consistently decreases with the lubricating oil usage for both phases of experiments. Calcium is added to lubricating oil as detergent inhibitor and dispersant. The possibility of calcium to originate from wear of the engine parts is almost negligible. Hence in both phases of experiments calcium concentration reduces with usage.

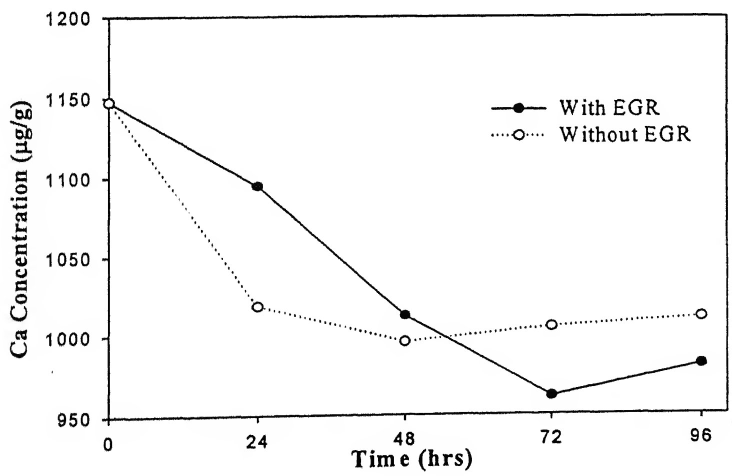


Figure 4.14 Ca Concentration as a Function of Lubricating Oil Usage

Similar results for zinc and calcium are also reported by Palus, [39]. Cadman and Johnson, have estimated wear elements in lubricating oil of 15% EGR system [33].

They showed a significant rise in wear element concentration and suggested that soot acts as an abrasive to remove the anti-wear surface coating by oil additives on the surfaces.

4.2.2. Soot Loading of Lubricating Oil

Diesel engine combustion process produces high amount of carbonaceous material known as soot. A part of this soot mixes with the lubricating oil and gets washed away to the oil sump. Thus the soot gets mixed with lubricating oil with the usage of oil. Another source of soot in lubricating oil is blow-by gases. This addition of soot in the diesel engine leads to increase the viscosity of lubricating oil.

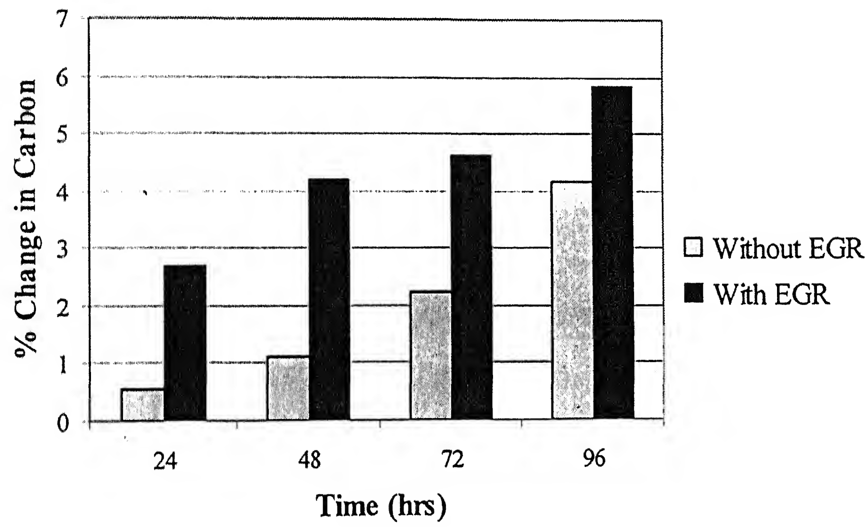


Figure 4.15: Percentage Change of Carbon w. r. t. Fresh Oil as a Function of Lubricating Oil Usage

When the lubricating oil was analyzed for carbon in the Total Organic Carbon (TOC) Analyzer, it has been found that lubricating oil has no inorganic carbon. The lubricating oil was also analyzed for total carbon. It is also assumed that lubricating oil does not undergo any chemical changes during the engine run. Hence the change in amount of carbon content gives a fair idea of soot present in the lubricating oil.

The initial carbon concentration in the lubricating oil was about 88%. The percentage variation in carbon content of the lubricating oil with oil usage is shown in figure 4.15. From the figure, it is clear that rise in carbon concentration is more in the lubricating oil drawn from engine using EGR system. For initial 48 hours of engine run, the rise in carbon content is more in lubricating oil drawn from engine operating on EGR. The high level of carbon in the lubricating oil of EGR system supports high smoke opacity

and soot density results reported in section 4.1.2. This high level of carbon (in other words, soot) in the EGR system causes increased wear of the vital engine parts and is confirmed by detection of metallic concentration in the lubricating oil.

Andrews *et al.*, have found that for a single cylinder IDI engine the carbon content rises up to 1.6% by weight over the 120 hours test period [43]. In the present study the carbon content rises up to 6% with EGR and 4% without EGR after 96 hours of engine run.

4.2.3 Carbon Deposition on Vital Engine Parts

Both phases of engine experiments were executed under similar conditions. The fuel and the lubricating oil used in both sets of experiments were same. The engines were run in similar load cycles for 96 hours. The physical conditions of various vital engine parts which are directly exposed to combustion of cylinder liner1 are shown in the figures from 4.16 to 4.21. Figure 4.16 shows carbon deposits on the piston head of EGR system and figure 4.17 shows carbon deposits on piston head of normally operated engine. It can be clearly seen that carbon deposits on the piston head of engine with EGR system is significantly more than that of normal operated engine.

Figure 4.18 shows carbon deposits on injector tip of EGR system after 96 hours of engine run. Figure 4.19 shows the carbon deposits on injector tip of normally operated engine after 96 hours of operation. On comparing these figures it is evident that the amount of carbon deposits on the injector tip of engine employing EGR are more as compared to injector tip of normally operated engine.

Figure 4.20 shows the carbon deposits on piston crown of engine operated with EGR and figure 4.21 shows carbon deposits on piston crown of normally operating engine (without EGR). The figures show that in the EGR operated engine, carbon deposits are more than engine without EGR.

The same trend was found in the cylinder liner 2 from both the systems and the pictures are given in Appendix-A.

The carbon deposits on the in cylinder engine parts are more in the EGR system than normal operated engine due to higher soot formation. These pictures support the results obtained by smoke opacity and soot density.

4.3 Estimation of Wear of Engine Parts

The relative motion of engine parts lead to wear of moving surfaces in contact. When the engine runs, the piston rings and cylinder liner surface are in relative motion, which

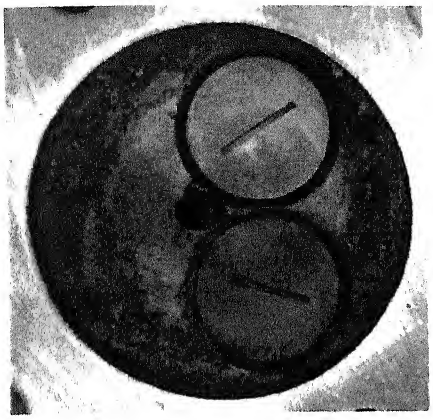


Figure 4.16: Carbon Deposits on the Cylinder Head of the Engine Using EGR

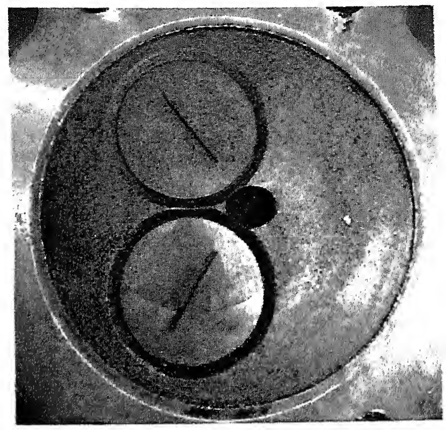


Figure 4.17: Carbon Deposits on the Cylinder Head of Engine Without EGR

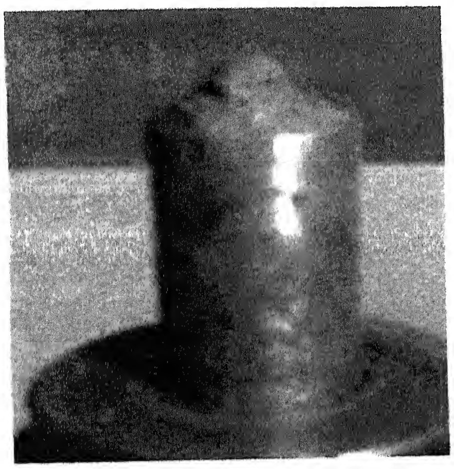


Figure 4.18: Carbon Deposits on the Injector Tip of the Engine Using EGR

Figure 4.19: Carbon Deposits on the Injector Tip of Engine Without EGR

Figure 4.20: Carbon Deposits on the Piston Crown of the Engine Using EGR

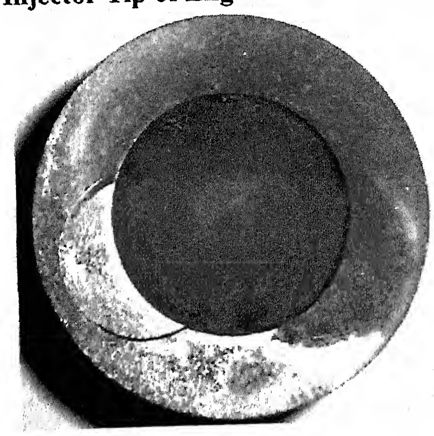


Figure 4.21: Carbon Deposits on the Piston Crown of Engine Without EGR

leads to wear of either of these surfaces. In this section, quantification of wear of piston rings, cylinder liners are discussed.

4.3.1 Wear of Piston Rings

The piston rings are one of the most important components in the engine, which are essential for operation of the engine. Piston rings are subjected to high thrust imposed by combustion gases. Rings are used to reduce the friction between cylinder liner surface and the piston. They are made of very high strength material so that they can resist high temperature and high thrust of combustion process and at the same time have very low wear.

In both phases of experiments, new rings are installed before starting the test run. The rings are weighed before the installation in the engine and after 96 hours of engine run. The percentage weight loss of rings in the cylinder liner 1 for both set of experiments has been shown in figure 4.22. A significant amount of weight loss of rings was observed after completion of test run. The weight loss of the rings takes place due to wear.

It has been observed that top compression ring of the engine operating without EGR has maximum weight loss among other compression rings. The loss in weight of top compression ring was approximately 0.50% of its initial weight. Top compression ring faces highest amount of thrust applied by combustion gases and is directly exposed to combustion process. Top ring always works in high temperature zone of cylinder liner. Hence, possibility of wear of top compression ring is maximum. The weight loss of oil ring was found comparable to top compression ring. The loss in weight of oil ring was also approximately 0.50%. The main function of oil ring is to scrap off excess oil from the cylinder liner surface and push it back to oil sump. This scrapped oil contains wear debris and it gets mixes with the lubricating oil in the oil sump. This oil is again recirculated to the various engine parts where these wear debris present in lubricating oil act as abrasive particles there by increasing the wear rate.

In the engine using EGR, top compression ring faces lowest weight loss compared to other rings. The weight loss of top compression ring is about 0.30% of the initial weight of ring. The oil ring faces highest amount of weight loss in the engine using EGR. The amount of wear was approximately 0.90% of initial weight.

It has been observed that the extent of wear of top ring in the engine using EGR is lower than normal operating engine. The possible reason of this may be the lower temperature of the combustion chamber of the engine using EGR. However, the wear

rate of second and third compression ring and oil ring is comparatively higher for engine using EGR. The possible reason for this may be presence of higher amount of soot and wear debris in the engine using EGR.

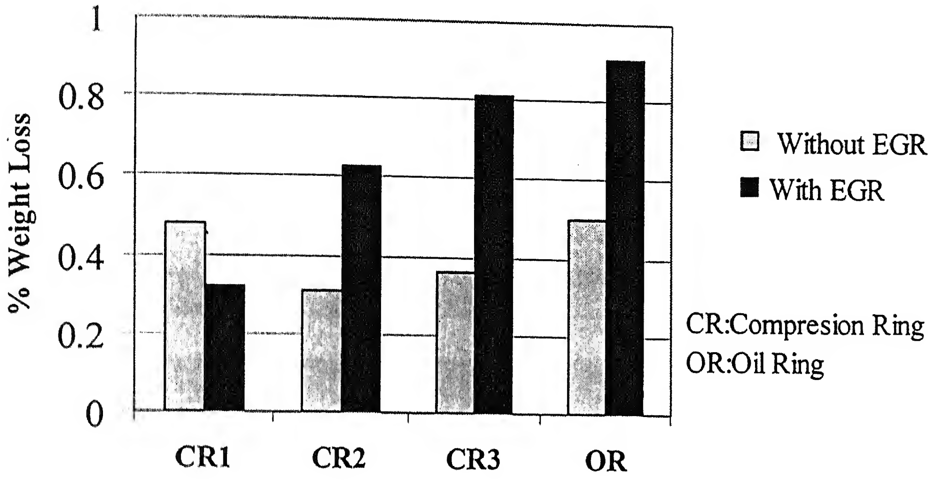


Figure 4.22: Wear of Piston Rings of Cylinder Liner 1

Similar results were obtained for piston rings of cylinder liner 2. The results are shown in Appendix-B.

4.3.2. Estimation of Wear of Cylinder Liners

The cylinder liners are made of high strength material so that it can withstand high pressure generated and wear due to extremely hot combustion gases. Scuffing and abrasion takes place due to three body relative motion of liner, piston rings and soot particles. Generally, cylinder liners are made of gray cast iron and alloys of nickel, chromium, copper and molybdenum are added to provide extra strength. The major reasons of liner wear are high thrust due to high pressure and temperature gases, abrasion due to soot and dust particles, poor lubrication etc.

New cylinder liners were used in both phases of experiments before the start of test. The surface profiles were taken at three locations (TDC, Mid Stroke, and BDC) of the liners on thrust and anti thrust side. After completion of test run surface profiles were taken at the same locations again. The evaluation length of the surface profile was kept 12.5mm. The profiles were taken with 10 times magnification in horizontal direction and 2000 times magnification in vertical direction.

The roughness parameters of cylinder liner 1 for engine operated without EGR on thrust and Anti thrust side are shown in Table 4.1 and surface profiles are shown in figure 4.23. From these roughness parameters shown in Tables 4.1 and surface profiles

shown in figure 4.23, it can be observed that the wear of the liner at TDC is consistently more than BDC and Mid Stroke positions.

Table 4.1 Roughness Parameters of Engine Operating Without EGR (Cylinder Liner1)

Parameter (µm)	Initial			After 96 hours of Engine Run		
	TDC	Mid Stroke	BDC	TDC	Mid Stroke	BDC
	Thrust Side					
Ra	0.9	0.74	0.8	0.75	0.50	0.60
Rq	1.15	0.94	0.99	1.03	0.78	0.64
Rt	7.18	4.95	5.27	6.49	6.98	7.37
Rp	3.42	2.60	2.34	0.98	1.81	1.24
Rv	3.76	2.35	2.93	5.51	5.17	6.13
	Anti Thrust Side					
Ra	0.81	0.87	0.79	0.49	0.65	0.58
Rq	1.03	1.16	0.98	0.99	0.76	0.77
Rt	7.79	9.72	6.01	7.57	6.67	4.87
Rp	3.97	2.97	2.41	1.35	1.77	1.02
Rv	3.82	6.75	2.96	6.22	4.9	3.85

The wear at TDC is more because this zone of cylinder liner faces highest temperature due to combustion gases. TDC faces high load, relatively lower piston speeds due to which boundary layer lubrication at TDC location break down. At TDC position, the lubricating oil film thickness is less than 0.025µm which is less than normal size of soot particles. So when soot particles get into the lubricating oil film, the soot particles act as abrasives and increase the wear of liner surface at TDC location.

It was also observed from Table 4.1 and figure 4.23 that wear of the cylinder liner is higher on the anti thrust side compared to thrust side. The possible reason of this may be the piston tilt during its stroke as shown in figure 4.24. In the four strokes of engine operation, the piston touches the thrust side of cylinder liner surface during intake stroke when temperature and pressure of engine are low. For the remaining three strokes the piston touches anti-thrust side of cylinder liner surface. Hence the wear at anti thrust side is more than thrust side.

The roughness parameters of thrust side and anti thrust side of cylinder liner 1, from the engine operated with EGR are shown in Table 4.2. The roughness parameters of TDC, Mid Stroke and BDC positions are compared in Table 4.2 and the profiles shown in

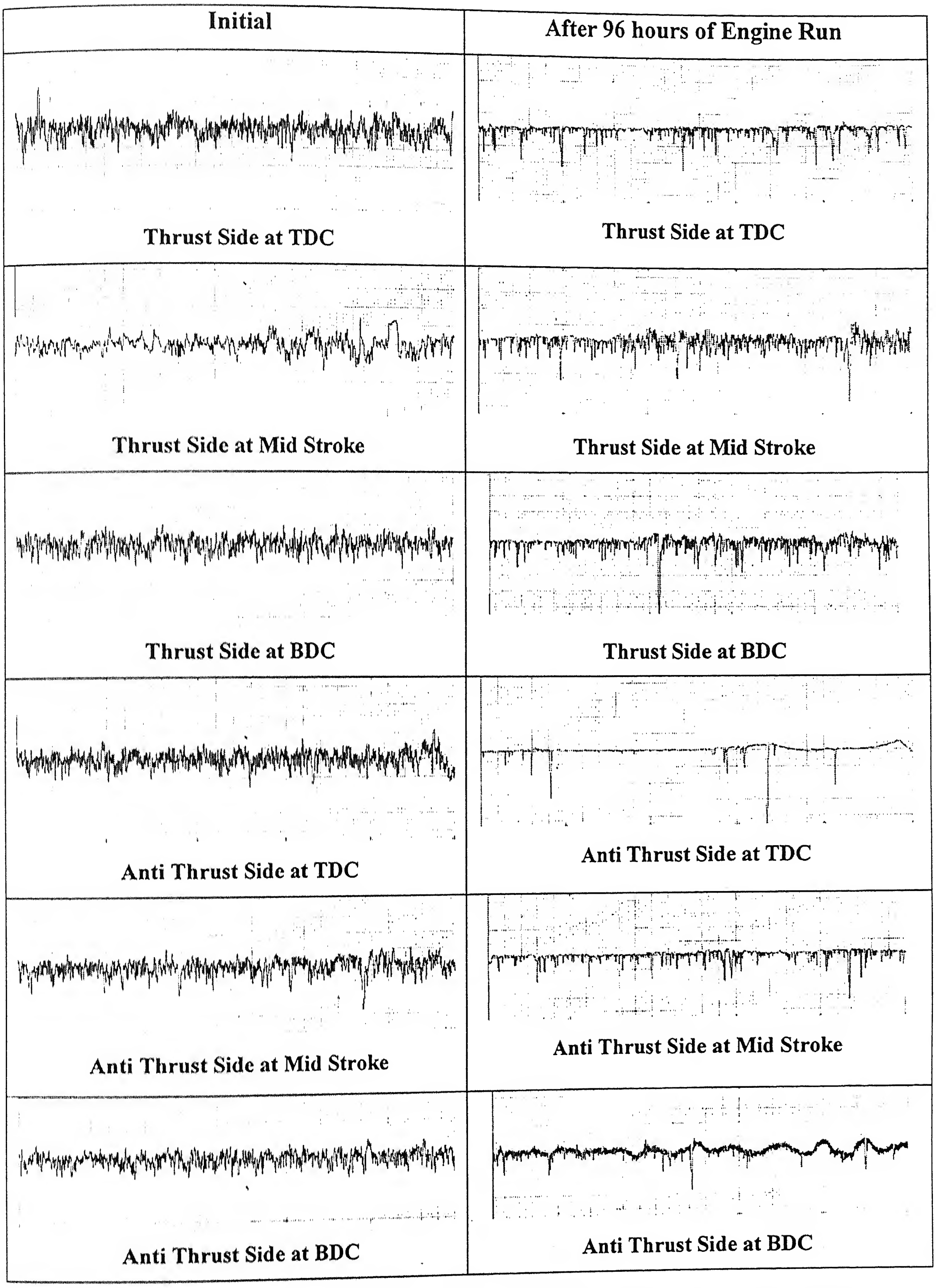


Figure 4.23: Surface Profiles of Cylinder Liner 1 of Engine Operating without EGR

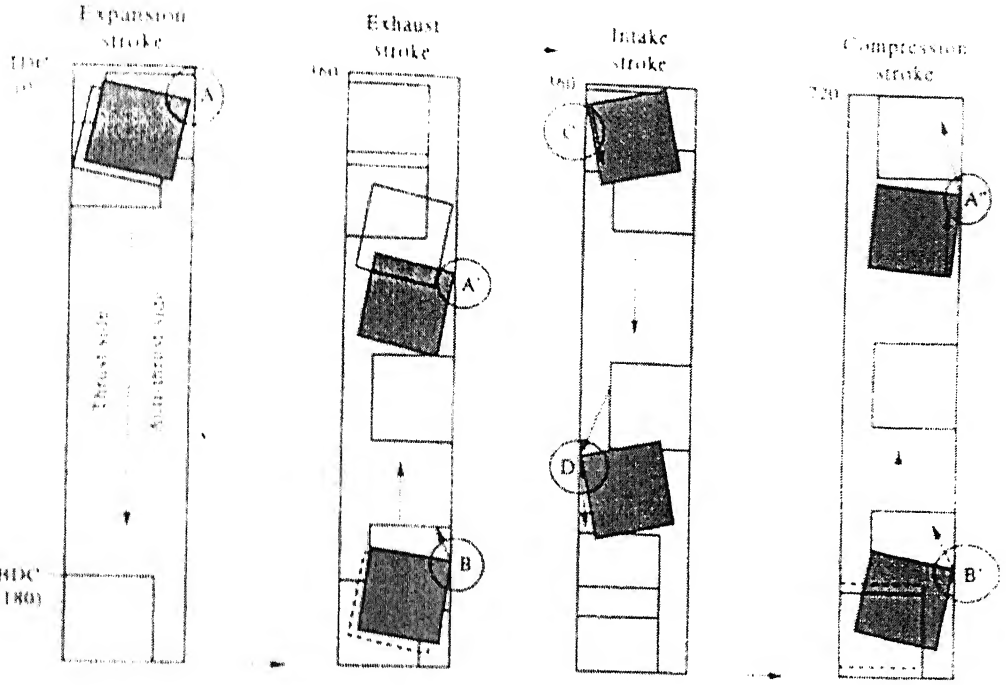


Figure 4.24: Schematic Representation of Piston Motion [46]

figure 4.25. It is observed that at BDC position the liner, maximum wear takes place. Minimum wear is observed at TDC location.

The maximum wear takes place in BDC position in anti thrust side also. In the engine using EGR, the temperature inside the combustion chamber is relatively low, hence the power pack is exposed to less severe conditions causing wear at TDC on thrust side of the liner. While on anti-thrust side, since the piston touches the cylinder liner for three strokes (as shown in figure 4.24), so inspite of low temperatures, significant wear takes place.

In the EGR system maximum wear takes place at BDC in thrust side as well as in anti-thrust side. At BDC position, boundary lubrication exists and the lubricating oil of EGR system contains higher amount of soot and wear metals, which may also be responsible for excessive wear at BDC.

Similar results were obtained for cylinder liner 2. The results are shown in Appendix-C and appendix-D for both phases of experiments.

Bearing Area curve represents the material ratio of the profile as a function of level, where 'mr' values are plotted on the abscissa while the slice levels on the ordinate. Material ratio of the profile (mr) is defind as ratio of the material length (sum of the sections made by a line which is parallel to the mean line and intersects the profile

element at a given level) of the profile elements at a given level to the evaluation length. The slice level is defined as the depth from the highest peak.

Table 4.2 Roughness Parameters Engine operating with EGR (Cylinder Liner 1)

Parameter (µm)	Initial			After 96 hours of Engine Run		
	TDC	Mid Stroke	BDC	TDC	Mid Stroke	BDC
	Thrust Side					
Ra	1.18	1.02	1.34	0.66	0.34	0.2
Rq	1.57	1.38	1.9	0.87	0.59	0.37
Rt	12.00	11.03	17.05	5.31	4.57	3.45
Rp	3.57	3.5	3.78	1.8	0.67	0.37
Rv	8.25	7.54	13.27	3.51	3.9	3.08
	Anti Thrust Side					
Ra	1.72	1.23	1.08	0.47	0.6	0.16
Rq	2.59	1.61	1.45	0.65	0.85	0.34
Rt	21.98	11.16	12.54	5.27	5.43	3.53
Rp	10.76	3.44	2.97	2.2	1.23	0.36
Rv	11.22	7.71	9.57	3.07	4.2	3.17

From the bearing area curve it has been found that the extent of wear in the EGR system is more than normal operating engine. The engine operated with EGR has larger wear at BDC while normally operated engine faces larger wear at TDC. The maximum straight line portion of the curve shows smoother surface. The wear in the anti thrust side is more than thrust side in normal operating engine while in EGR operated engine the wear is almost same in thrust and anti thrust side.

Bearing Area Curve (BAC) of each surface was also taken for each location. Figure 4.9 shows the BAC of thrust and anti thrust side surfaces for with EGR and normal Operating engine.

The BAC for these surfaces on liner 1 and liner 2 on thrust and anti thrust side for both phases of experiments are given in Appendix E.

Bae, *et al.*, have studied the effect of EGR on wear rate of the cylinder liner [47]. They found that the wear in the mean wear rate of cylinder liner with EGR was greater in the measurement positions of the second half than those of the first half. In the present study the wear at BDC was found maximum.

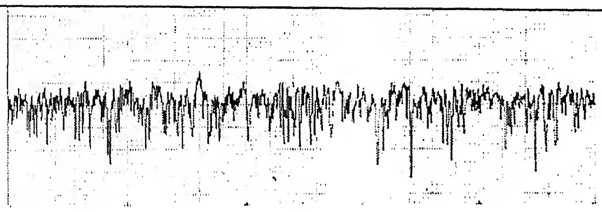
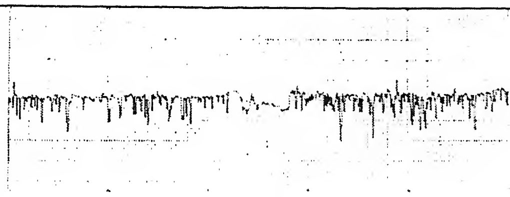
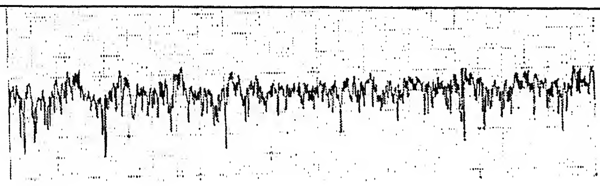
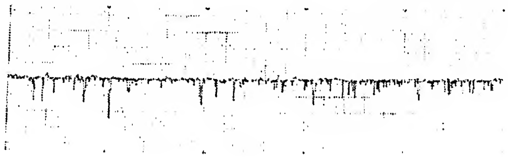
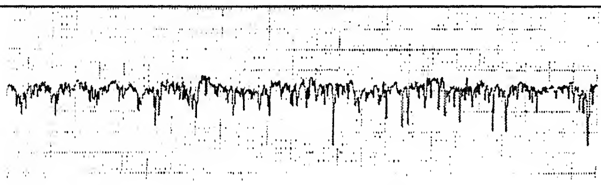
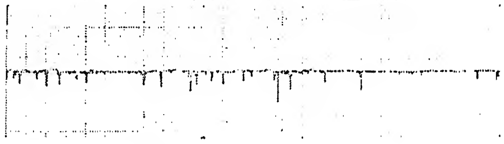
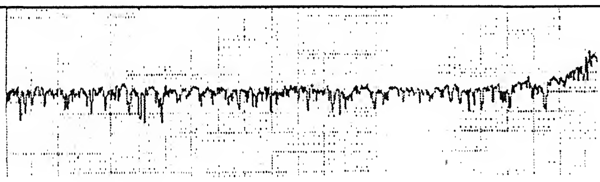
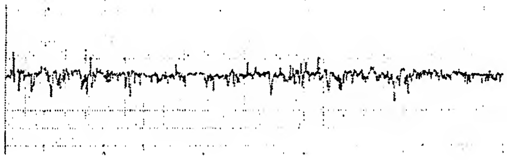
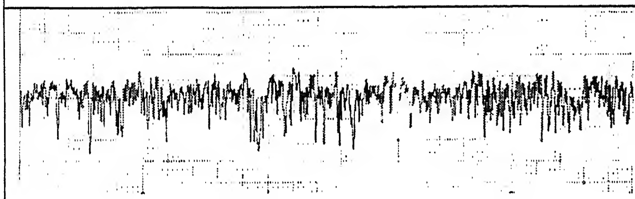
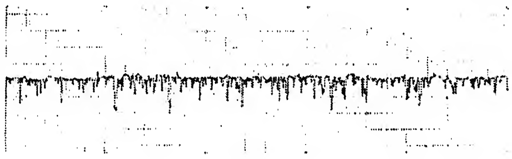
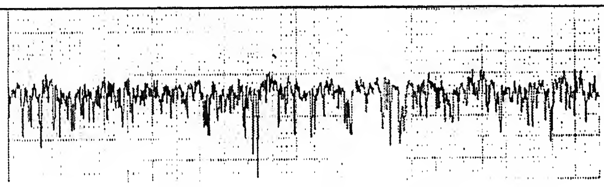
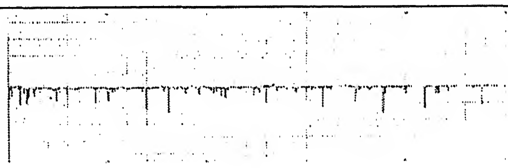
Initial	After 96 hours of Engine Run
 Thrust Side at TDC	 Thrust Side at TDC
 Thrust Side at Mid Stroke	 Thrust Side at Mid Stroke
 Thrust Side at BDC	 Thrust Side at BDC
 Anti Thrust Side at TDC	 Anti Thrust Side at TDC
 Anti Thrust Side at Mid Stroke	 Anti Thrust Side at Mid Stroke
 Anti Thrust Side at BDC	 Anti Thrust Side at BDC

Figure 4.25: Surface Profiles of Cylinder Liner 1 of Engine Operating with EGR

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

Major species of concern from the diesel engine exhaust are oxides of nitrogen and particulate matter. For reduction of pollutant coming from diesel engines, various techniques are being used. Exhaust Gas Recirculation (EGR) is a very useful technique for reducing the NO_x emission. In the present research, experimental investigation was conducted to study the performance of a diesel engine using EGR and the effect of EGR on engine wear.

For conducting the experiments, a constant speed, two cylinders, four stroke, direct injection, air cooled, diesel engine (Indec PH2 model) equipped with an AC generator set of 9kW rating was chosen. The experiments were conducted in two phases. In the first of experiments, the engine tests were executed at normal operating engine condition (i.e. without EGR) and in the second phase of experiments the experiments were conducted at a fixed EGR rate of 25%. In both phases of experiments, the engine was run with a predetermined engine load cycle. The engine was run for 96 hours in each phase. Results of both the phases are compared to study the performance of EGR with respect to normal operating engine.

5.1 Conclusions

The performance of engine running under EGR and without EGR conditions in the two separate phases of experiments was compared for engine exhaust, lubricating oil and wear on engine parts to analyze the effect of EGR on these.

The exhaust gas temperature, smoke opacity and soot density of the exhaust gases were measured in both phases of experiments. The exhaust gas temperature reduction and increase in smoke opacity (i.e. soot density) indicates reduction in NO_x and rise in soot in diesel engine exhaust. This phenomenon is dominant for higher engine load. This observation decisively concludes that with the use of EGR, reduction in NO_x can be achieved without significant increase in exhaust particulate matter.

The samples of lubricating oil were drawn from the lubricating oil sump after every 24 hours interval from the engine in both phases of experiment. The lubricating oil was tested for the heavy metal addition and the soot loading as a function of usage of the lubricating oil. The oil samples were analyzed for Fe, Cu, Cr, Al, Ni, Zn, Mg, Pb, Ca

and Mn additions for both phases of the experiment Except Zn and Ca, all other metals have shown increasing trend with the use of oil in both phases of experiments. The rise in concentration of each metal was found to be higher in initial engine run and then the rate of heavy metal addition to the lubricating oil stabilizes. The engine using EGR always showed higher metal content than engine operating without EGR. The most probable reason for this higher metal content in the lubricating oil from EGR operated engine may be higher soot formation in the oil.

In order to confirm this, lubricating oil samples were also analyzed for soot loading as a function of the engine usage. Soot loading in lubricating oil of EGR operated engine was found to be approximately 2% higher than the engine operating without EGR, confirming the hypothesis.

A qualitative analysis of soot formation was also done by taking pictures of in-cylinder engine parts. Higher soot deposition was observed on cylinder head, injector tip, and piston crown of EGR operated engine than without EGR operated engine.

Wear of the piston rings and cylinder liner was estimated. The wear of top compression ring in the engine operated with EGR was found to be significantly lower than the engine operated without EGR. But the wear of oil ring in the engine operated with EGR was approximately 0.5% more than that of the engine operating without EGR. Higher wear was observed at BDC on anti-thrust side in EGR operated engine while higher wear was observed at TDC of anti-thrust side in the engine operated without EGR.

It was concluded from this study that with the use of EGR, we can achieve good amount of exhaust gas temperature reduction, thereby reduction in formation of NO_x. The biggest penalty of EGR system is the rise in formation of particulate matters. The rise in particulate matters leads to poor engine performance in term of faster lubricating oil degradation and higher wear of vital engine parts. The soot control along with EGR is the key for improved emissions in terms of soot and NO_x emissions from the engine.

5.2 Scope for Future Work

Measurement of actual emission pattern can be done in order to optimize the amount of EGR required at various engine loading conditions and to quantify the amount of various gaseous pollutants.

The composition of soot particles of exhaust may be analyzed in order to check the effect of EGR on the soot compositions. The soot particles may be analyzed for heavy metals content and also for Poly Aromatic Hydrocarbon (PAH) species adsorbed by it.

Engine performance can be analyzed after employing soot trap in order to reduce the soot emissions as an exhaust post-treatment measure. The performance of the soot trap and its effectiveness, need to be looked into more carefully before recommending their large scale usage. Also ways and means need to be identified to regenerate the soot traps. .

Effect of cooled exhaust recirculation can be evaluated by providing cooling measures to the re-circulating exhaust gas using exhaust gas heat exchangers.

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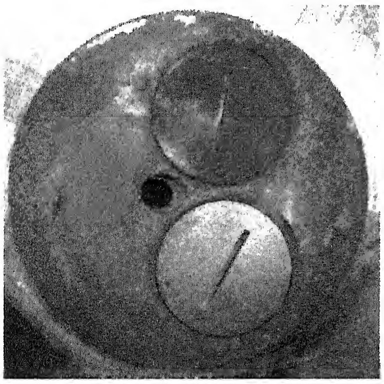


Figure A.1: Carbon Deposits on the Cylinder Head of the Engine Using EGR

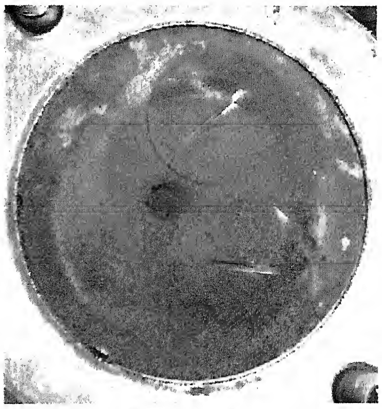


Figure A.2: Carbon Deposits on the Cylinder Head of Engine Without EGR

Figure A.3: Carbon Deposits on the Injector Tip of the Engine Using EGR

Figure A.4: Carbon Deposits on the Injector Tip of Engine Without EGR

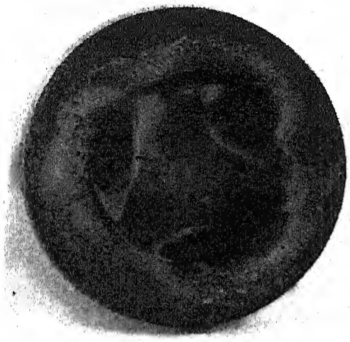


Figure A.5: Carbon Deposits on the Piston Crown of the Engine Using EGR

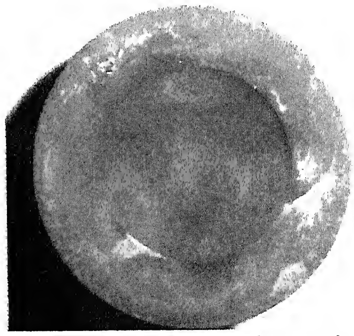


Figure A.6: Carbon Deposits on the Piston Crown of Engine Without EGR

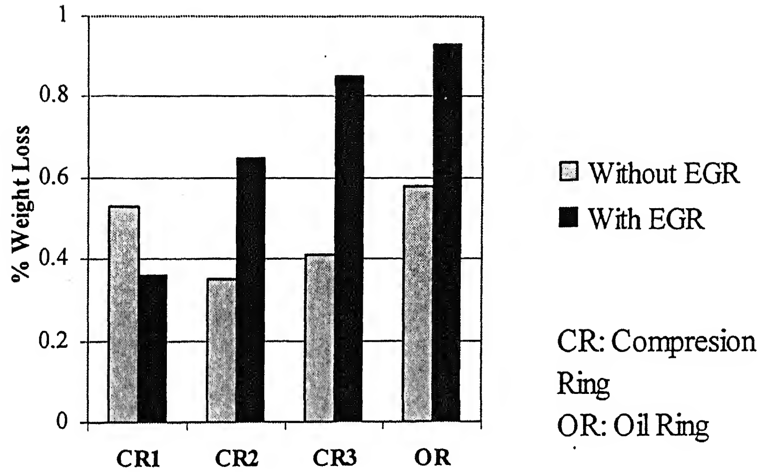


Figure B.1: Wear of Piston Rings of Cylinder Liner 2

C.1 Average Roughness (R_a)

The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length.

$$R_a = \frac{1}{L}\int_0^L |r(x)| \mathrm{d}x$$

R_a does not give a clear picture about a surface. For example, three surfaces that all have the same R_a are shown in figure 1.3. It is evident from the picture that they are quit different from each other. In some applications these surfaces will perform differently.

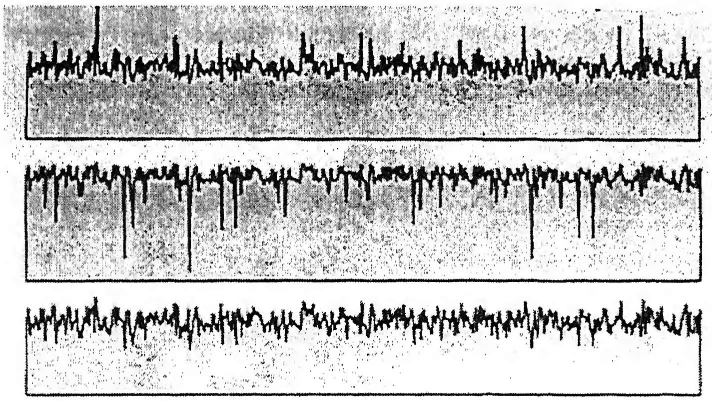


Figure C.1: Three Surfaces with Same R_a, but Different General Shapes

These three surfaces differ in the shape of the profile - the first figure has sharp peaks, the second has deep valleys, and the third has neither. Even if two profiles have similar shapes, they may have a different spacing between features. The following three surfaces also all have the same R_a.

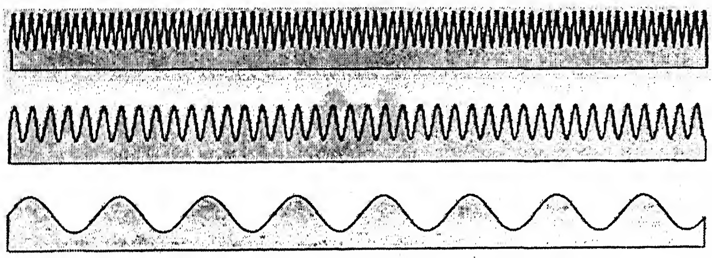


Figure C.2: Surfaces with Same R_a

Hence it is needed to distinguish between surfaces that differ in shape or spacing. Other parameters for a surface that measure peaks, valleys, profile shapes and spacing etc. need to be calculated.

C.2 Root Mean Square Roughness (R_q)

The root mean square (rms) average roughness of a surface is calculated from another integral of the roughness profile:

$$R_q = \sqrt{\frac{1}{L}\int_0^L r^2(x)\,dx}$$

For a pure sine wave of any wavelength and amplitude, R_q is proportional to R_a and it is about 1.11 times higher.

C.3 Peak Roughness (R_p), Total Roughness (R_t) and Depth of Deepest Valley (R_v)

The peak roughness (R_p) is the height of the highest peak in the surface profile over the evaluation length (P_1). Similarly, R_v is the depth of the deepest valley in the roughness profile over the evaluation length (V_1). The total roughness, R_t, is the sum of these two, or the vertical distance from the deepest valley to the highest peak.

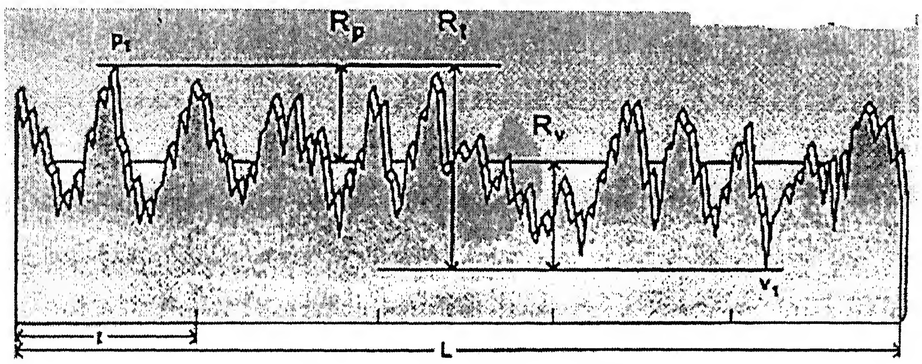


Figure C.3: Surface Profile

$$R_v = \left|\min\left[r(x)\right]\right|, \quad 0 < x < L$$

$$R_p = \left|\max\left[r(x)\right]\right|, \quad 0 < x < L$$

$$R_t = R_p + R_v$$

Table C.1: Roughness Parameters of Engine Operating Without EGR (Cylinder Liner 2)

Parameter (μm)	Initial			After 96 hours of Engine Run		
	TDC	Mid Stroke	BDC	TDC	Mid Stroke	BDC
	Thrust Side					
Ra	0.78	0.56	0.56	0.43	0.43	0.11
Rq	1.04	0.78	0.73	0.7	0.83	0.22
Rt	7.18	5.12	4.86	6.35	8.03	2.72
Rp	3.01	1.55	1.74	0.97	1.86	0.44
Rv	4.17	3.57	3.12	5.38	6.17	2.28
	Anti Thrust Side					
Ra	0.57	0.69	0.64	0.34	0.21	0.25
Rq	0.76	0.89	0.86	0.5	0.31	0.63
Rt	4.28	5.4	5.99	3.83	2.38	5.48
Rp	1.67	2.09	2.28	0.61	0.6	0.44
Rv	2.61	3.31	3.71	3.22	1.78	5.04

Table C.2: Roughness Parameters of Engine Operating With EGR (Cylinder Liner 2)

Parameter (μm)	Initial			After 96 hours of Engine Run		
	TDC	Mid Stroke	BDC	TDC	Mid Stroke	BDC
	Thrust Side					
Ra	1.01	0.96	1.04	0.33	0.3	0.13
Rq	1.41	1.31	1.38	0.53	0.5	0.25
Rt	15.03	12.65	10.9	4.28	4.32	3.02
Rp	3.73	3.47	3.72	0.66	0.64	0.49
Rv	11.3	9.18	7.18	3.62	3.68	2.53
	Anti Thrust Side					
Ra	1.09	1.19	1.25	0.43	0.52	0.19
Rq	1.49	1.65	1.66	0.62	0.75	0.44
Rt	10.91	12.7	14.62	3.92	5.17	4.37
Rp	2.62	3.12	4.16	0.87	0.88	0.36
Rv	8.29	9.57	10.46	3.05	4.29	4.01

Appendix D: Surface Profiles of Cylinder Liner 2

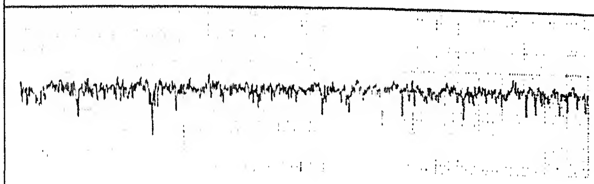
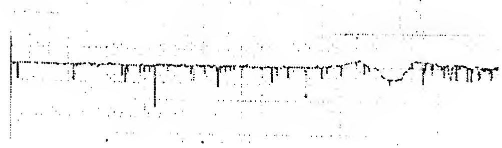
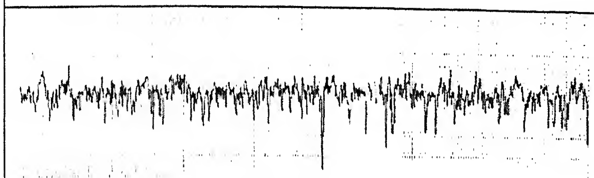
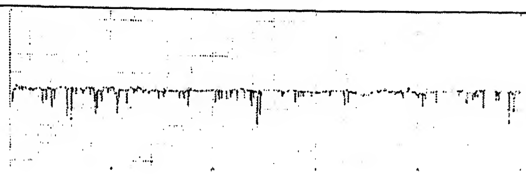
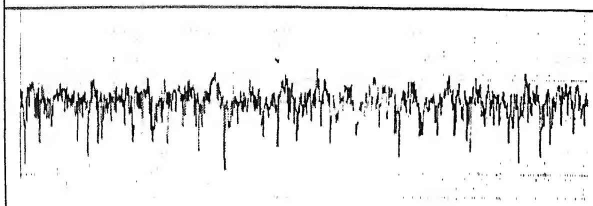
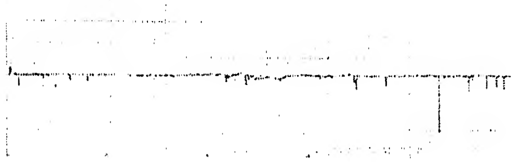
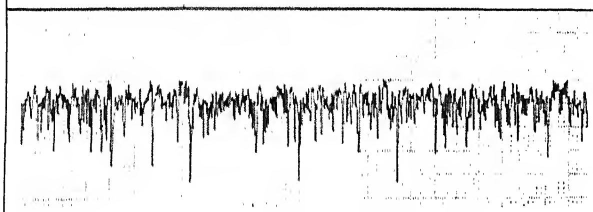
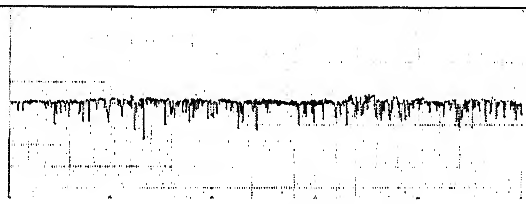
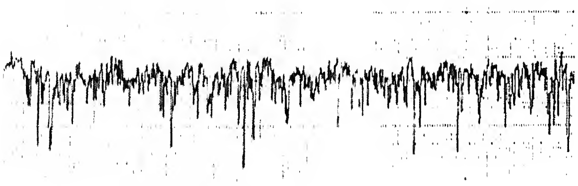
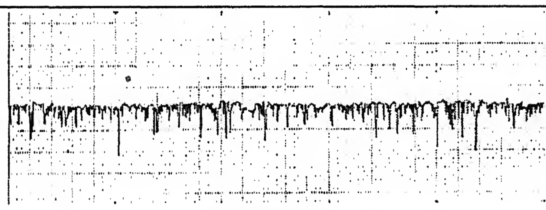
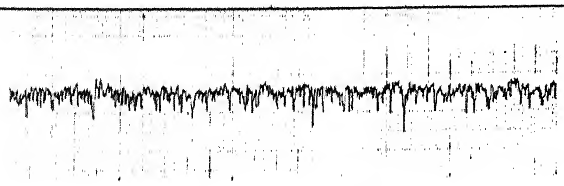
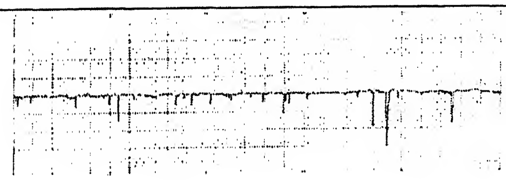
Initial	After 96 hours of Engine Run
 Thrust Side at TDC	 Thrust Side at TDC
 Thrust Side at Mid Stroke	 Thrust Side at Mid Stroke
 Thrust Side at BDC	 Thrust Side at BDC
 Anti Thrust Side at TDC	 Anti Thrust Side at TDC
 Anti Thrust Side at Mid Stroke	 Anti Thrust Side at Mid Stroke
 Anti Thrust Side at BDC	 Anti Thrust Side at BDC

Figure D.1: Surface Profiles of Cylinder Liner 2 of Engine Operating without EGR

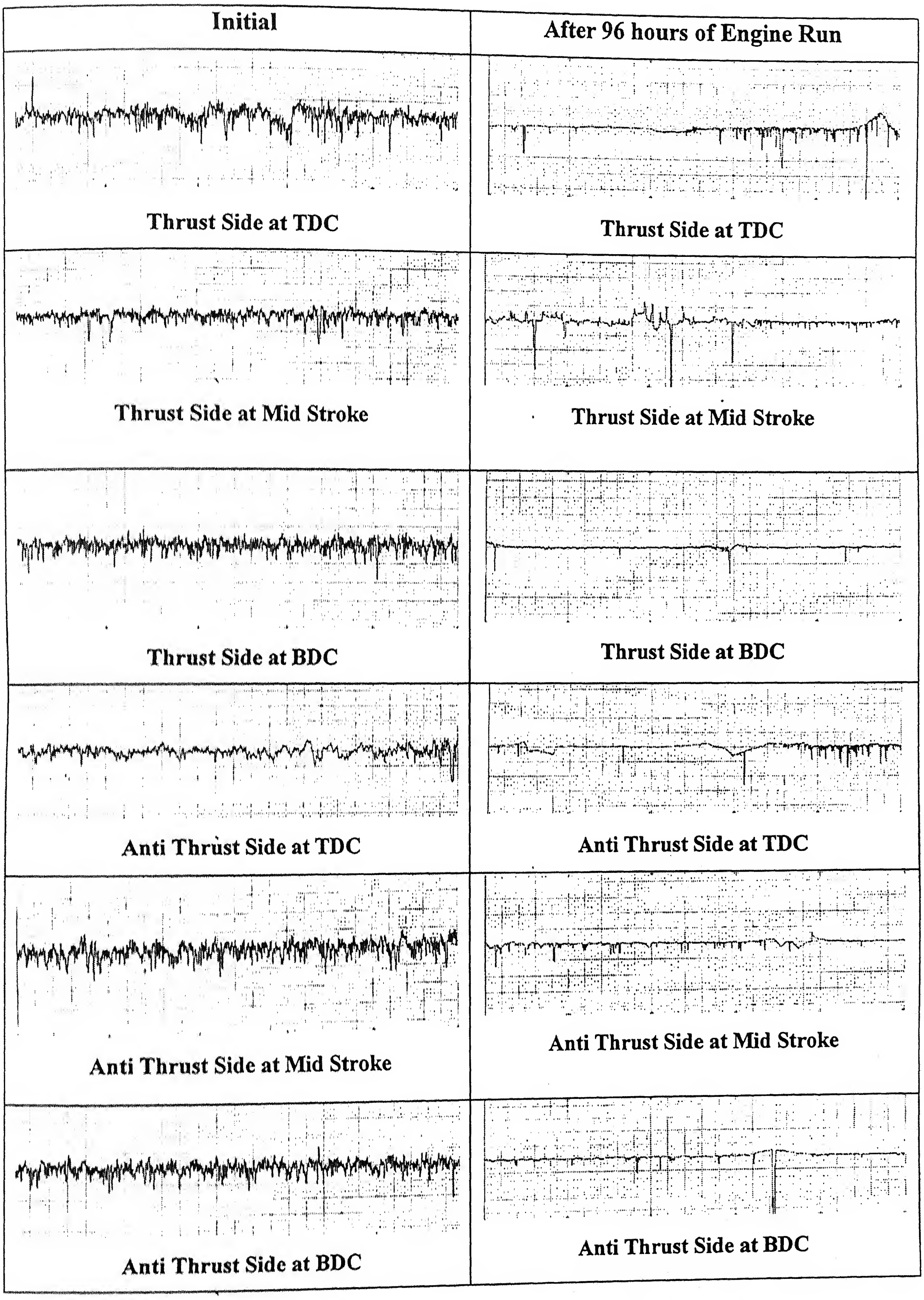


Figure D.2: Surface Profiles of Cylinder Liner 2 of Engine Operating with EGR

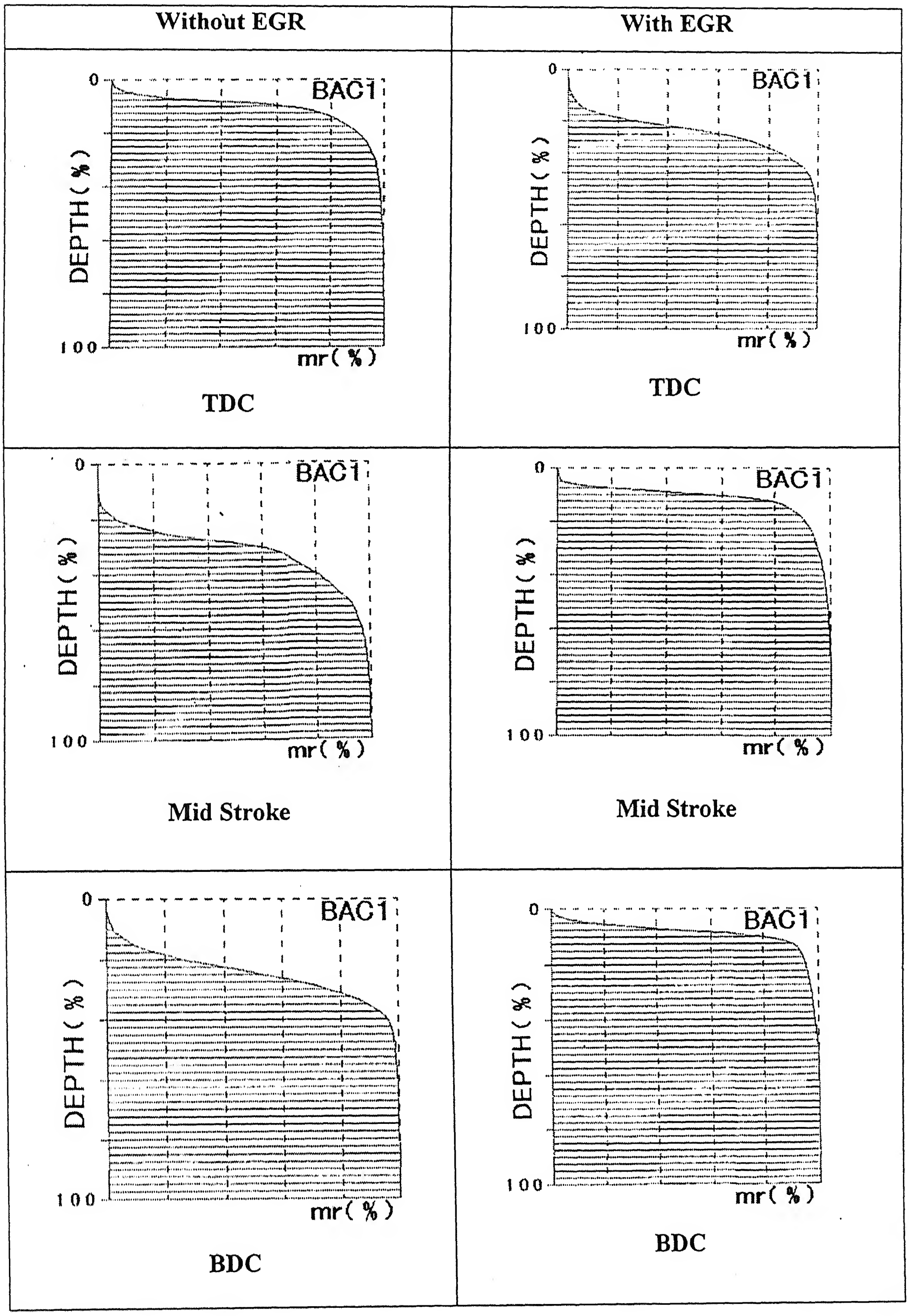


Figure E.1: Bearing Area Curve of Cylinder Liner 1 after 96 hours of Engine Run (Thrust Side)

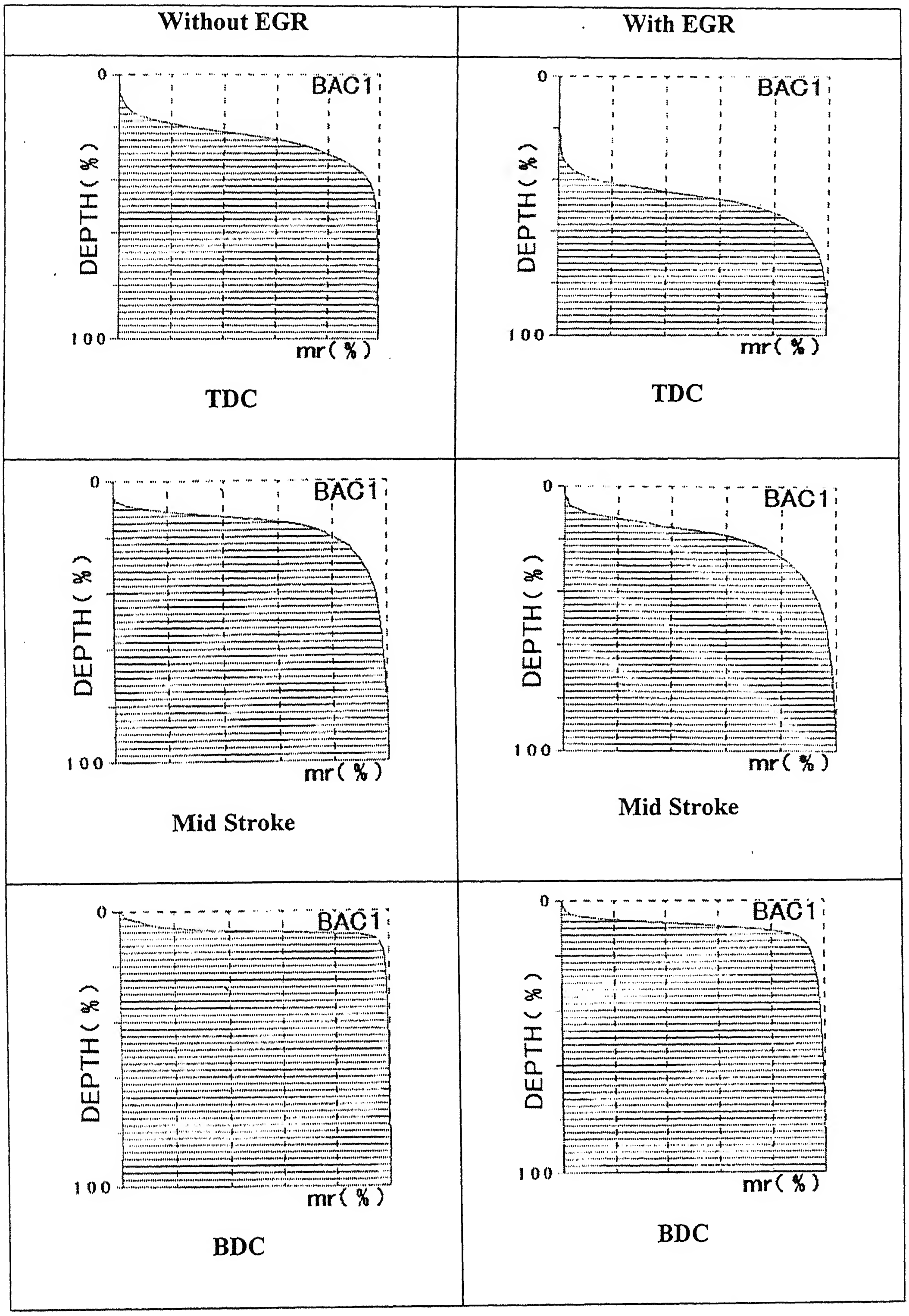


Figure E.2: Bearing Area Curve of Cylinder Liner 1 after 96 hours of Engine Run (Anti-Thrust Side)

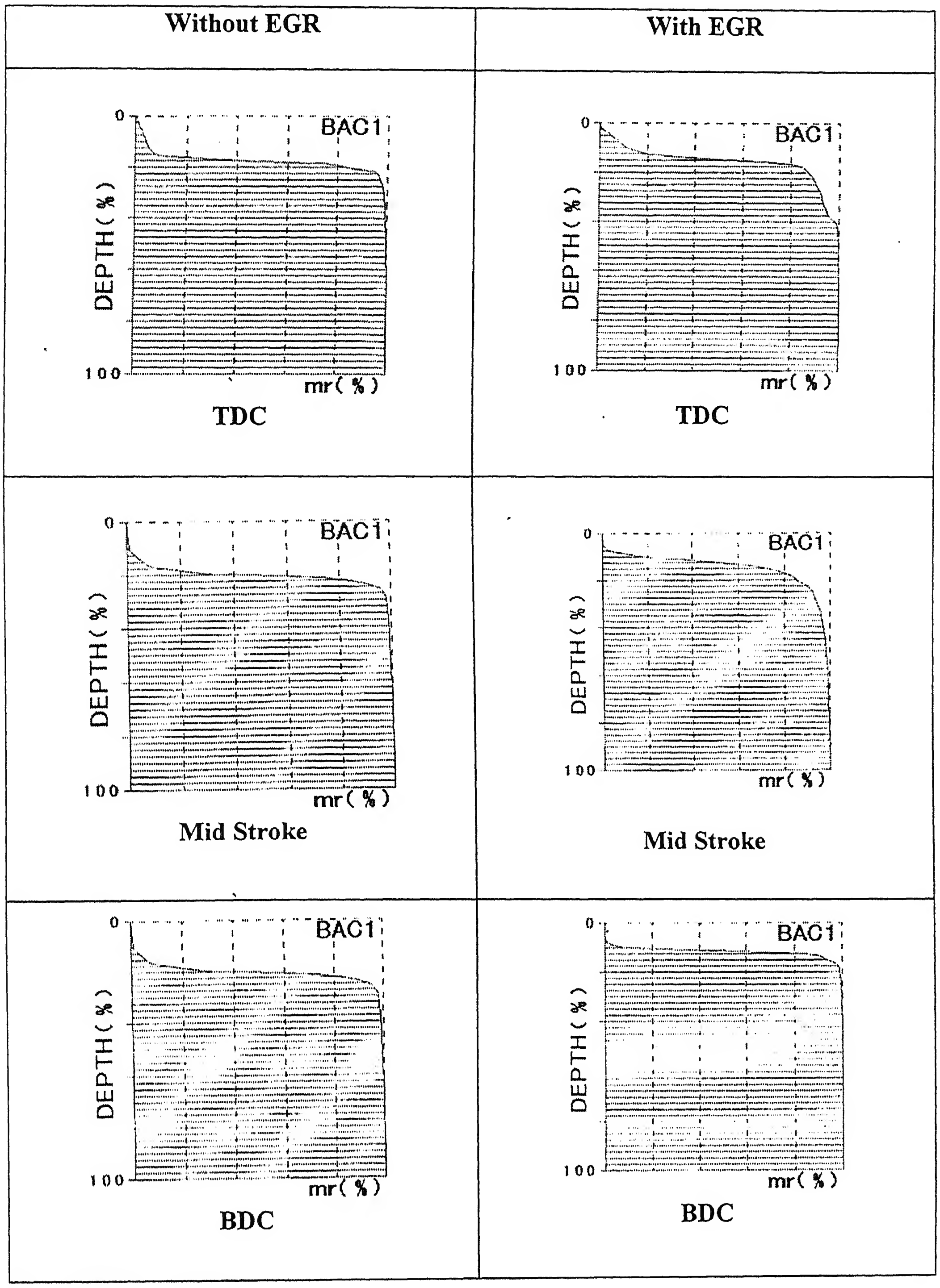


Figure E.3: Bearing Area Curve of the Cylinder Liner 2 after 96 hours of Engine Run (Thrust Side)

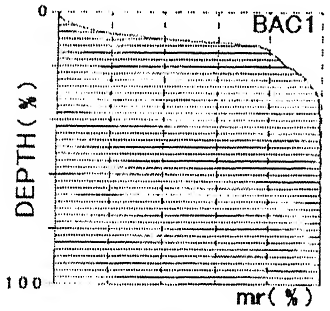
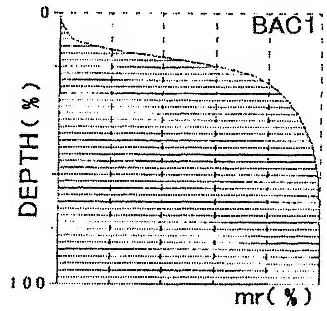
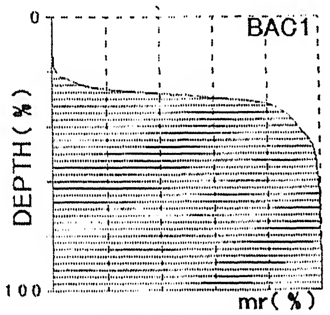
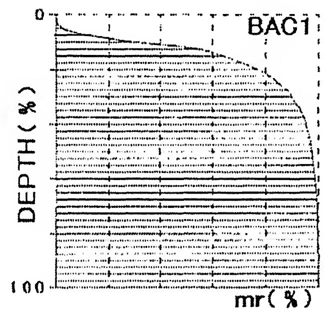
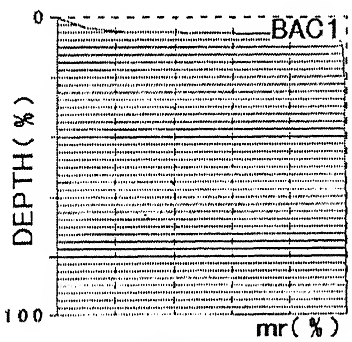
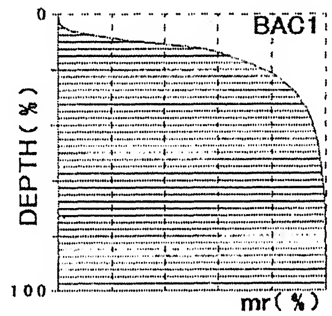
Without EGR	With EGR
 TDC	 TDC
 Mid Stroke	 Mid Stroke
 BDC	 BDC

Figure E.4: Bearing Area Curve of the Cylinder Liner 2 after 96 hours of Engine Run (Anti-Thrust Side)